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MASTERCLASS 08

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"Alternativas a los tratamientos biologicos convenionales de la EDAR."

Oriol Carbó

Técnico de I+D+i en GS INIMA

GS Inima

III Ciclo de 20 MasterClass

AGUASRESIDUALES.INFO

Jueves

22 MAYO

16:30h. España

- **Empresa con una posición sólida en la industria de tratamiento de agua en todo el mundo**
- Más de 60 años en el mercado:

1968 1970 1995 1998 2007 2009 2011 2014 2019 2020 2021 2023 **2024**

  - 1968 Primera planta desaladora del mundo por ósmosis inversa en Cabo Verde
  - 1970 Primera desaladora en España (Lanzarote)
  - 2009 Mayor planta de secado térmico en España: Metrofang
  - 2011 Mayor planta de biofiltración de Europa: E.D.A.R. Lagares

- Actúa en todas las fases de los proyectos : **Financiación, Ingeniería, Suministro, Construcción, Operación y Mantenimiento**
- Posicionada como una de las empresas con mayor número de plantas en modalidad concesional

GS INIMA ENVIRONMENT. PRESENCIA MUNDIAL

GSI - INNOVAMOS PARA NUESTROS CLIENTES

GSI cuenta con un equipo cualificado para investigar, proponer y pilotar proyectos innovadores y diferenciadores, con el **objetivo de ser más eficientes y competitivos.**

FOWE® en IDAM de Alicante II

OSCAR en EDAR Numancia de la Sagra

PRONOX ® en EDAR La Garriga

PROGRAMOX ® en EDAR La Garriga

ROWSIP® en IDAM de Ensenada (México)

MICROPLÁSTICOS

Uso de microorganismos específicos para la biodegradación de microplásticos en una EDAR

ROWSIP®

"Reverse Osmosis With Simple Intake and Pretreatment" (Instalado en Desaladora Ensenada)

OSCAR

Oxidación Húmeda de la materia orgánica de fangos de depuración

DC-SOIAS

Desionización capacitiva de salmueras de plantas desalobradoras

FOWE ®

Recuperación de energía de la salmuera de una planta de desalación de agua de mar a través de membranas de ósmosis de directa

PRONOX ®

Bases de diseño y control del proceso HRAS, como tratamiento previo a los Lodos Activos, en sustitución de la decantación primaria

PROGRAMOX ®

Diseño y desarrollo de un prototipo de reactor Anammox a escala semi-industrial para operar a continuación de los procesos HRAS y AGS en la línea de agua

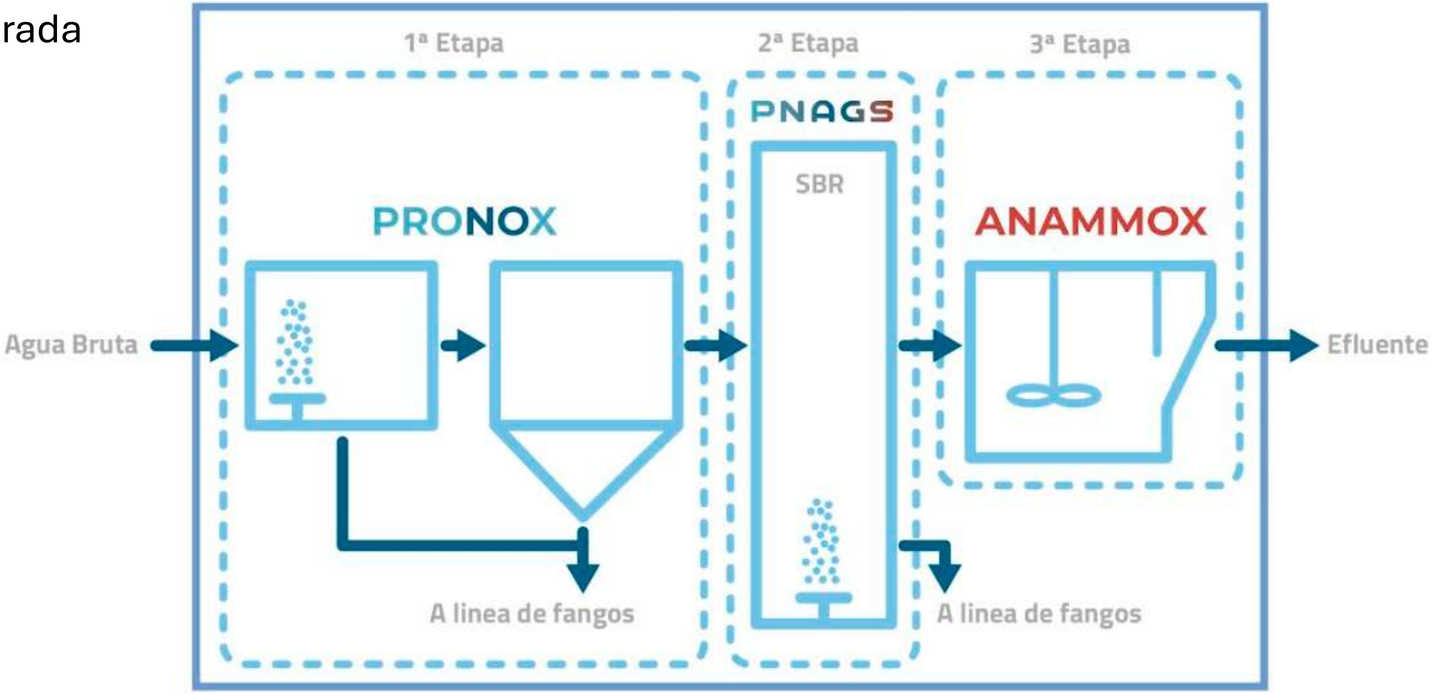
GEMELO DIGITAL

Optimización de las plantas de tratamiento a través de la inteligencia artificial mediante el desarrollo de un Gemelo Digital cognitivo

PROGRAMOX

by GS Inima

- ✓ Marca registrada
- ✓ Patente



Desarrollado conjuntamente con lequia UdG ECO-INNOVATIVE ENVIRONMENTAL SOLUTIONS, Universitat de Girona

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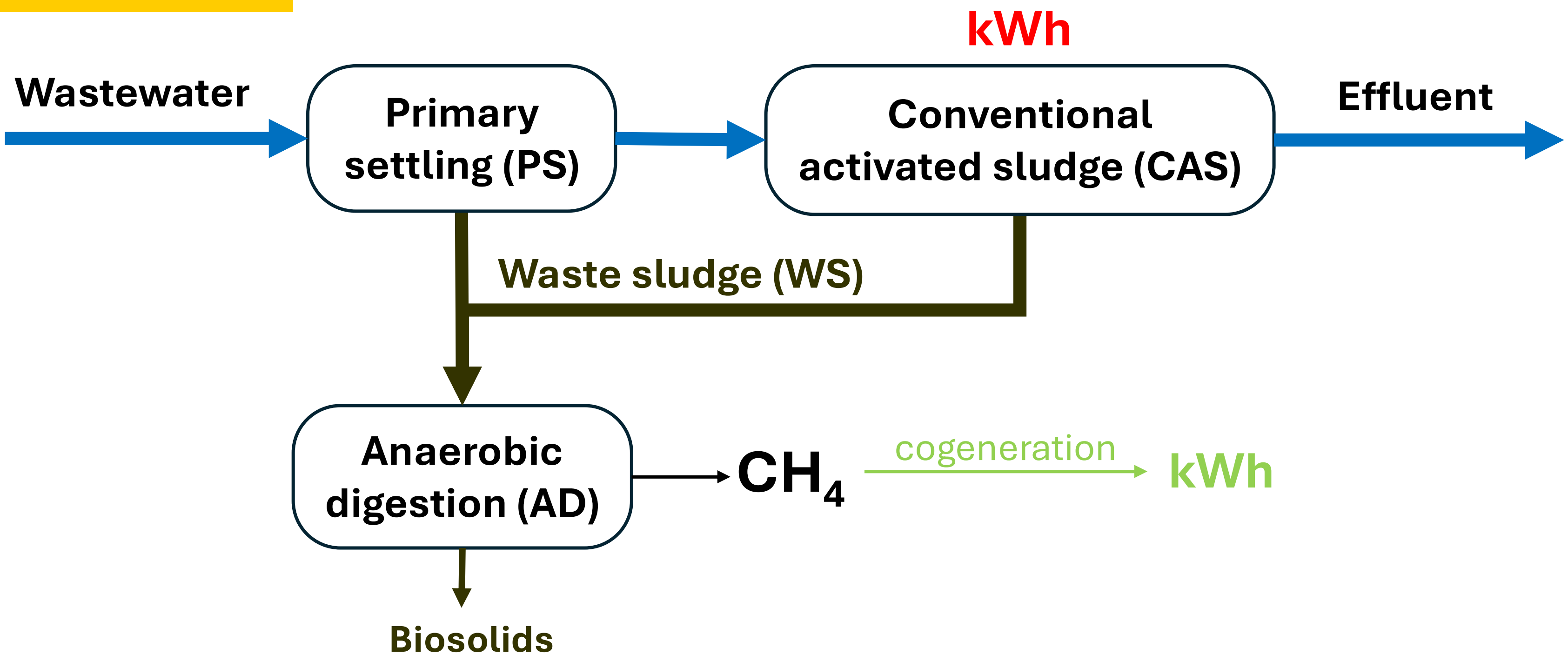
1. INTRODUCTION

Conventional WWTPs



- **PS** + **CAS**-based configurations predominate
- **AD** to produce CH_4

- **Energy consumption** (aeration, pumping, etc.)
- **Energy recovery** (CH_4 cogeneration)

Energy consumption in WWTPs

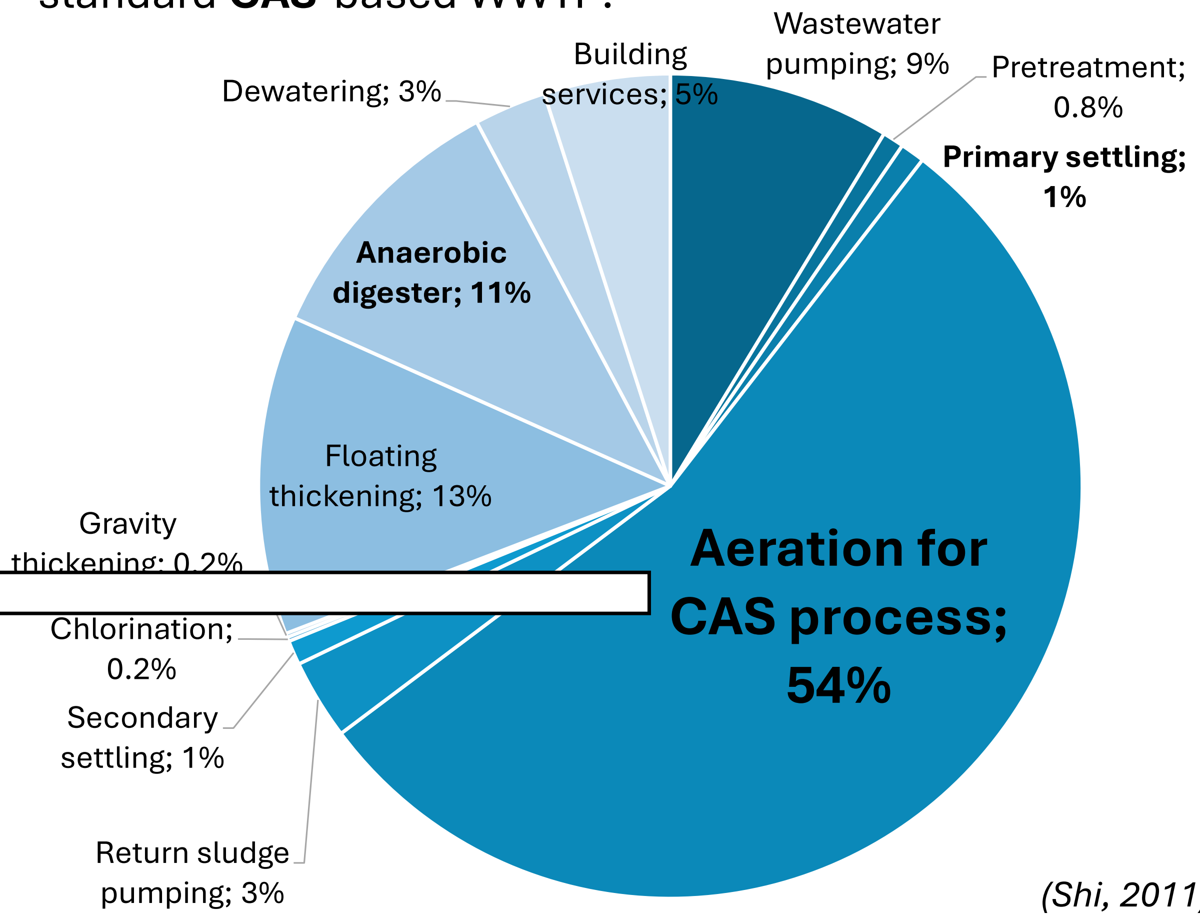
Specific treatment consumption:
- Catalonia: **0.452 kWh/m³** *(ACA, 2021)*
- World: **0.3-0.6 kWh/m³** *(Wan et al., 2016)*

WWTPs consumption vs. country electricity consumption *(USEPA, 2007)*:
- United States: **3%**
- Others: up to **5%**

- ❑ **2/3** for **COD** oxidation
- ❑ **1/3** for **N** oxidation

❖ Efficient approach: **aeration reduction**

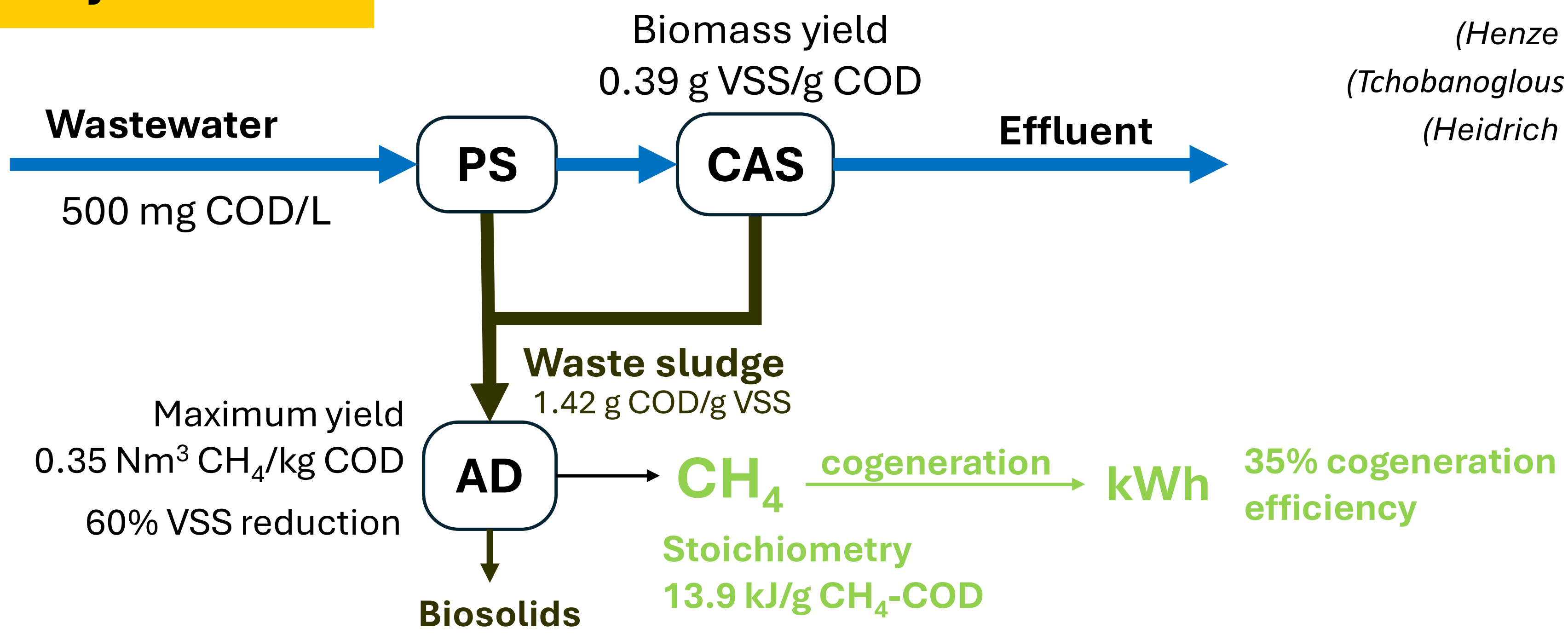
- Energy consumption distribution in a standard **CAS**-based WWTP:



(Shi, 2011)

Energy recovery in WWTPs

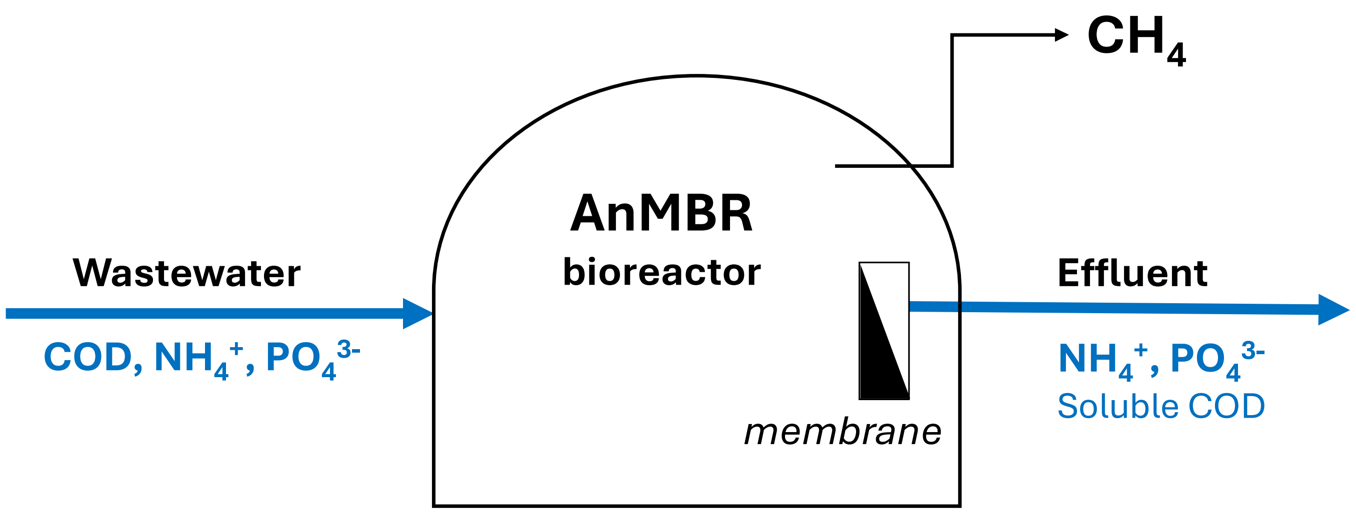
(Henze et al., 2008)
(Tchobanoglous et al., 2014)
(Heidrich et al., 2011)



- **Feasible recovery: 0.22 kWh/m³**
  (i.e., 49% of consumption –*0.45 kWh/m³*–)

- **How can energy recovery be enhanced?**
  - Mainstream AD
  - Increase COD redirection to AD

Mainstream **anaerobic membrane bioreactor (AnMBR)**



Liu et al. (2014)

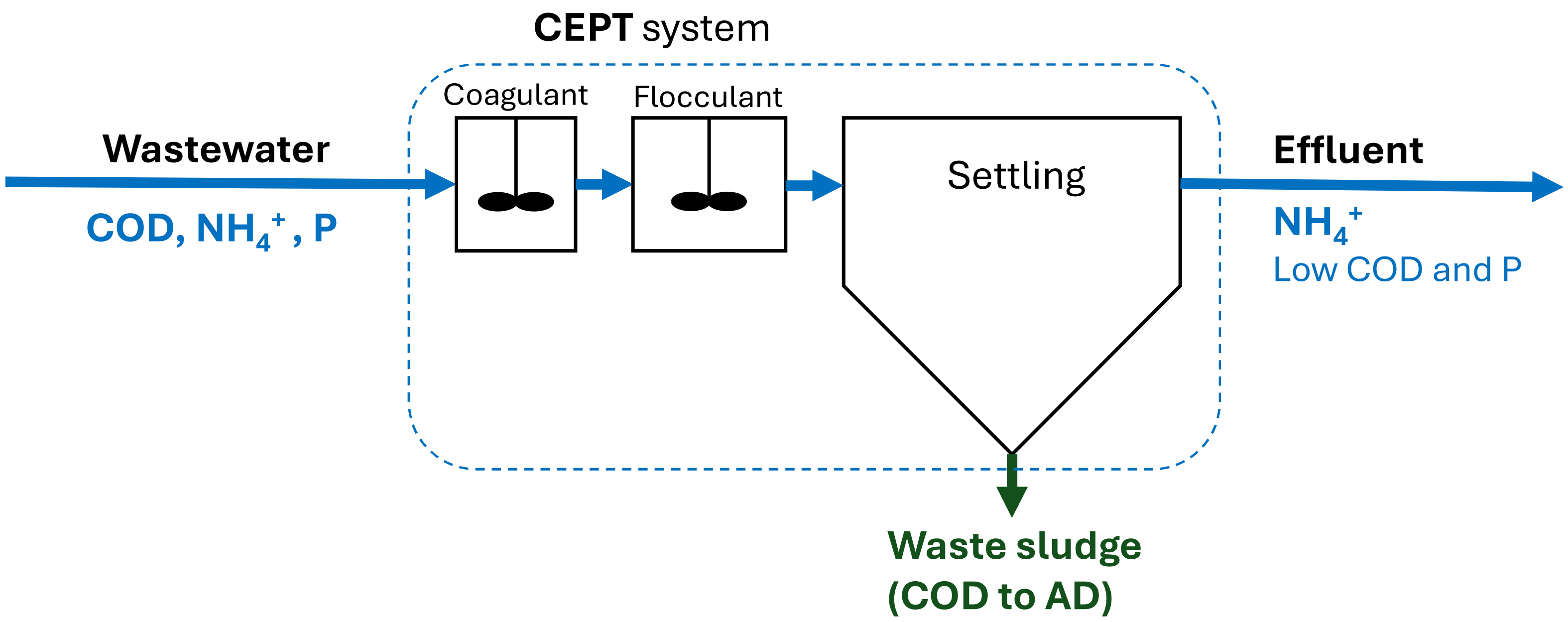
PROS

✓ Direct anaerobic COD conversion to CH_4

CONS

- Dissolved CH_4 in the effluent (50% of the produced CH_4)
- High energy filtration cost
- AD effluent with (high) soluble COD

COD redirection to AD: chemically enhanced primary treatment (CEPT)



- Chemical process, no biological activity

PROS

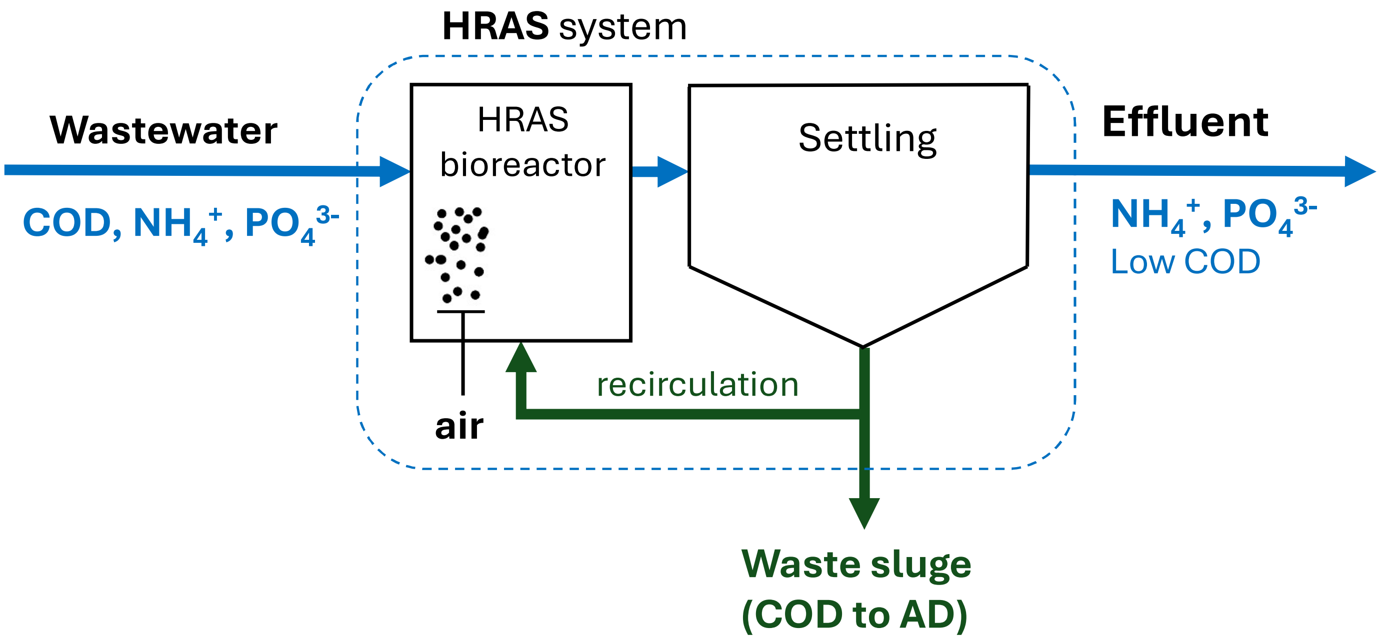
✓ High removal efficiency:
70-80% COD, 90% TSS, 90% P
(Diamantis et al., 2011)

CONS

- Addition of chemical products
- High volume of sludge

COD redirection to AD: High-rate activated sludge (HRAS)

(Canals et al., 2023)



- Biological process, but:
  High load & low SRT
  - ❑ HRT < 1 h, SRT < 1 d

  Low DO consumption
  - ❑ 0.5 – 1.0 mg DO/L
- Based on **sorption** and **bioaccumulation** rather than oxidation

PROS

- ✓ No chemical products addition
- ✓ Higher COD removal (55-65%) than PS (30-40%)
- ✓ Colloidal COD removal

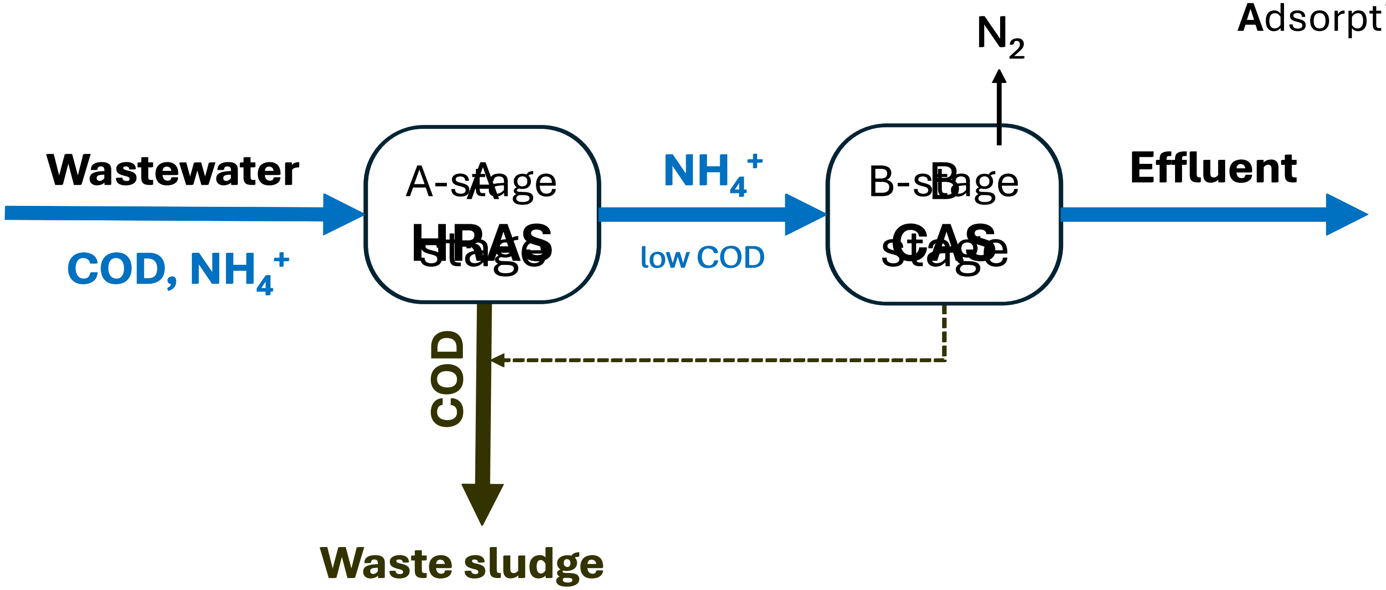
CONS

- Lower COD removal than CEPT (55-65% vs. 80-90%)
- Fraction of COD oxidation (but small)

COD redirection + nutrient removal: A/B process

Adsorption/**B**io-oxidation (1970s)

(Böhnke B., 1977)



EU effluent requirements (WWTPs > 150,000 p.e.):
TN < 10 (8) mg/L
(E. parliament, 2024)

B-stage:
- Different configurations based on CAS
- Low influent COD
- Enough SRT to achieve BNR (N, P)

Problem: COD/N too low for denitrification

Alternative CAS: aerobic granular sludge (AGS)

- Developed lab-scale in **1990s** *(Morgenroth et al., 1997)*
- Real implementation in **2006**, Nereda® *(Pronk et al ., 2017)*

Characteristics *(de Kreuk et al., 2007)*:

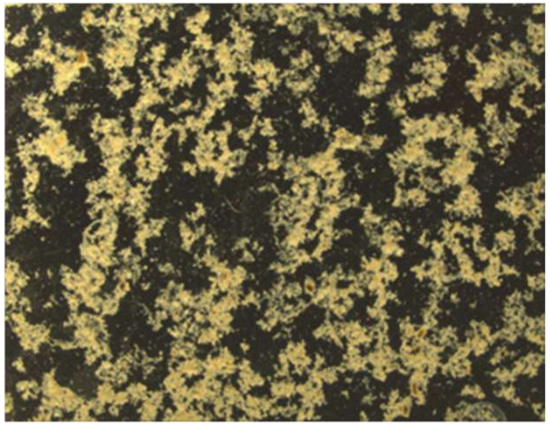
- Minimum diameter of 0.2 mm
- $SVI_{10}/SVI_{30} \approx 1.0$
- Nitrifiers grow on granule surface
- Polyphosphate accumulating organisms (PAO) grow inside the granules

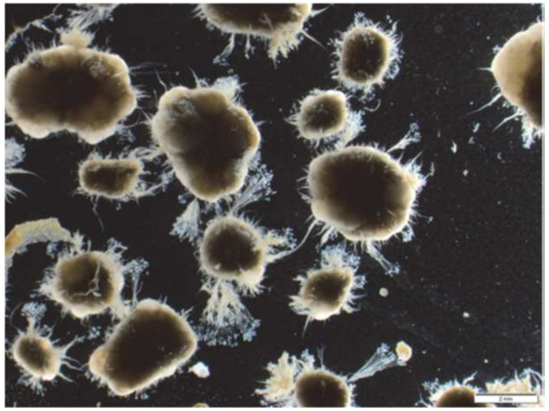
➢ Sequencing batch reactor (**SBR**) operation

✓ **Lower footprint**
Fast-settling and high-thickening properties eliminates the need for secondary clarifiers

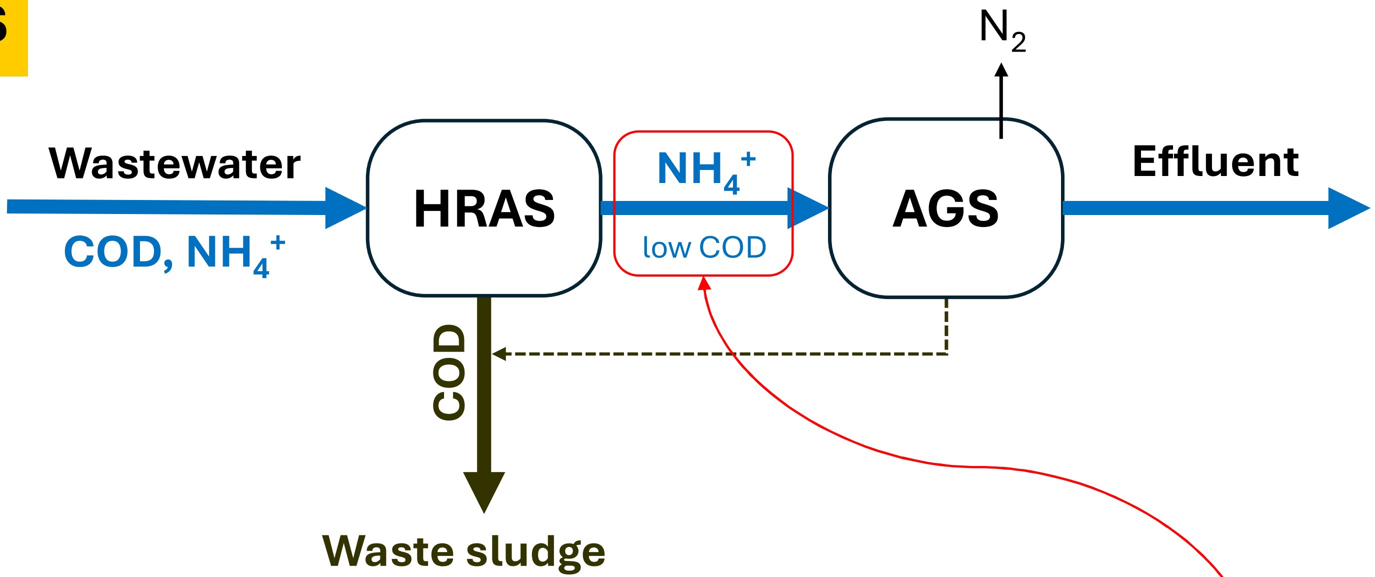
✓ **Lower energy consumption**
Recycling flows and mixers avoided

Pronk et al., 2020





HRAS + AGS



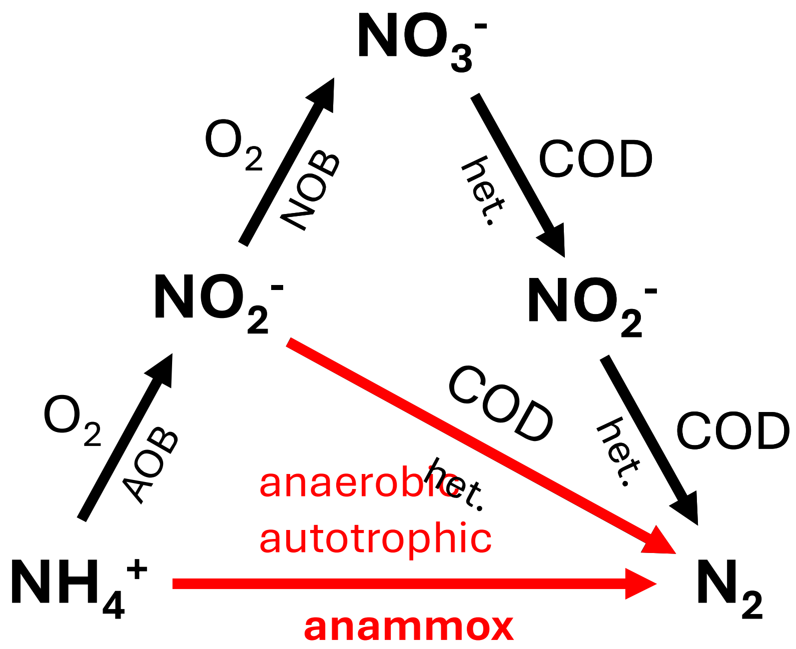
Novel approach

- AGS at low organic loading rate (OLR) *(Pronk et al., 2015)*
- HRAS+AGS only one recent lab-scale study available *(Kosar et al., 2023)*

- Potential difficulties in heterotrophic denitrification (A/B problem)

✓ Niche for **mainstream autotrophic N removal**

Nitrogen removal



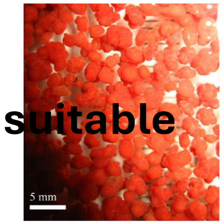
Predominates in CAS and AGS

Process	Nitrification: O_2 demand (g O_2/g N)	Denitrification: COD demand (g O_2/g N)	O_2 balance (g O_2/g N)
Conventional **nitrification – denitrification**	4.57	2.86	1.71
Nitritation – denitritation (**via nitrite**)	3.43	1.71	1.72
PN-anammox	1.72	0	1.72

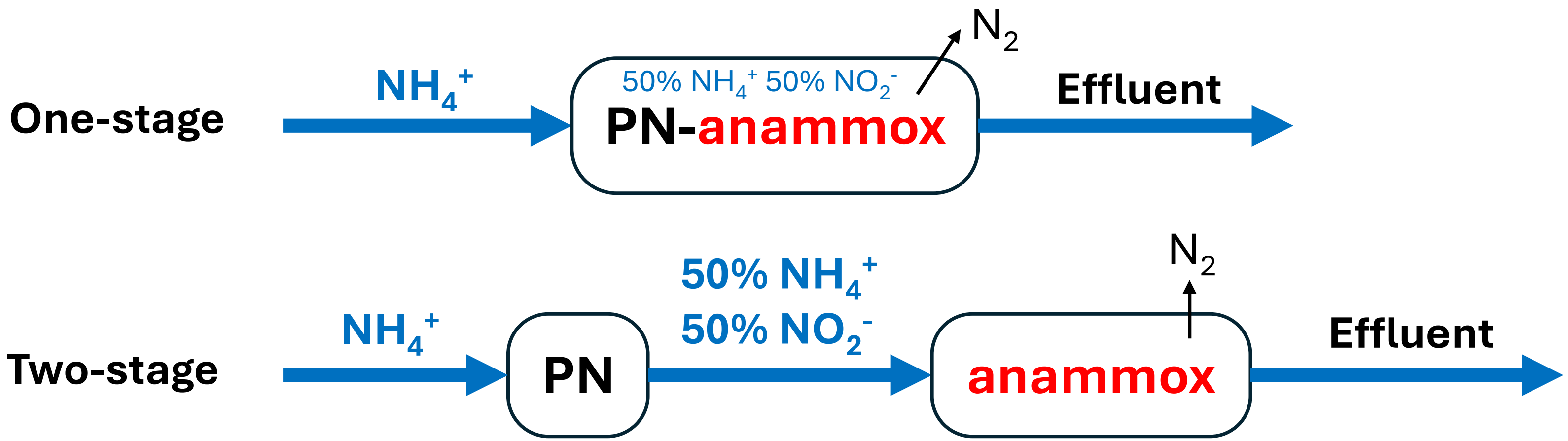
AOB: ammonium oxidising bacteria
NOB: nitrite oxidising bacteria
het.: heterotrophic denitrifiers
anammox: anaerobic ammonium oxidation

- If COD available, O_2 requirements are similar
- If **COD not available** (A-B process), **PN-anammox suitable**

partial nitritation (PN) – anammox; **PN-anammox**; **PNA**; **autotrophic N removal**



Mainstream autotrophic N removal: partial nitritation anammox (PNA)



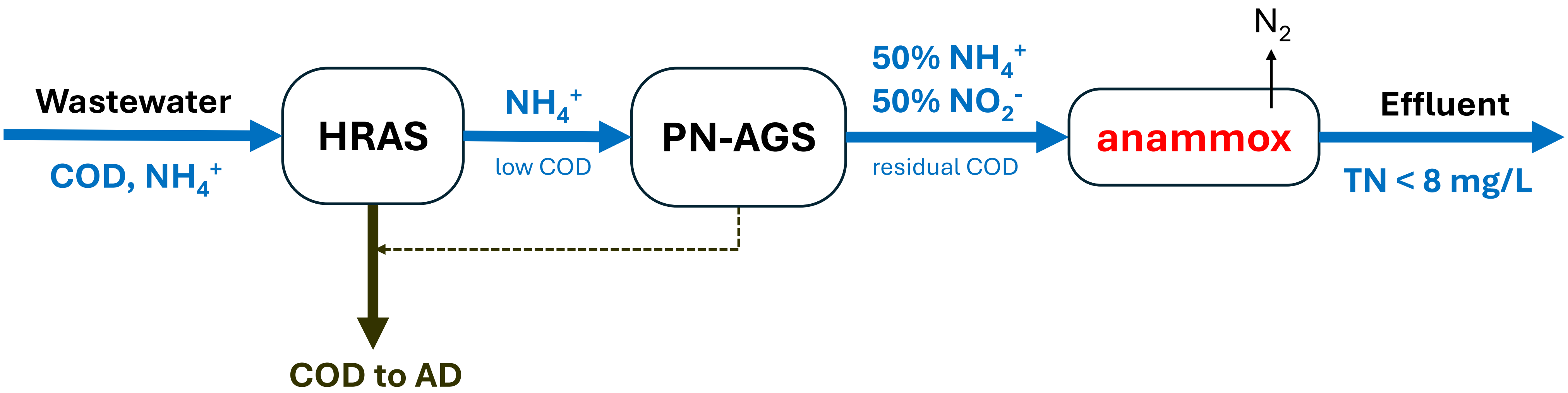
Separated <u>control</u> of the <u>PN</u> and <u>anammox</u> processes

Not fully implemented yet

Literature review

	Scale	PNA configuration	Problem for implementation
Hausherr et al., 2022	Pilot-scale	Two-stage	• Unknown NOB repression mechanism
Pedrouso et al., 2023	Pilot-scale	Two-stage	• Lack of long-term stability demonstration
Podmirsed et al., 2022	Full-scale	One-stage	• Constant sidestream anammox inoculation • Costly hydrociclones
Cao et al., 2017	Full-scale	One-stage	• Only at 30ºC

HRAS + two stage PNA (with AGS): process proposal



HRAS

- Already implemented; stable process

PN-AGS

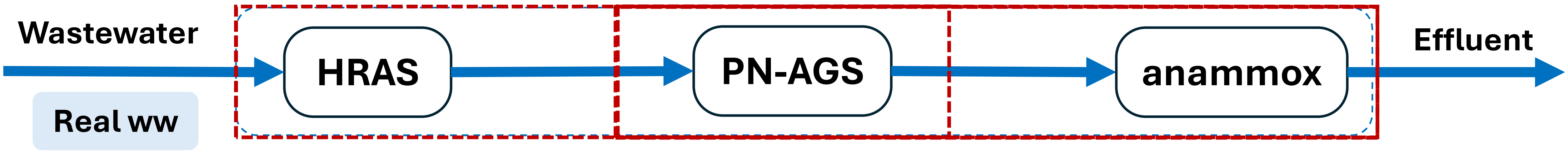
- Few lab-scale studies combining AGS with COD removal and PN *(Zhao et al., 2023)*

anammox

- Effluent quality needs to be assessed

Objectives

- Study a new **mainstream configuration** for urban WWTPs: HRAS + PN-AGS + anammox (**PROGRAMOX**®)



1) Identify a suitable strategy to **achieve AGS**

2) **Achieve partial nitritation** with AGS

3) **Control** and **performance** of the combined PN-AGS + anammox process

4) **Energy balance** to compare PROGRAMOX® vs. La Garriga CAS

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3. METHODOLOGY

RESULTS AND DISCUSSION

4. Aerobic granulation from HRAS

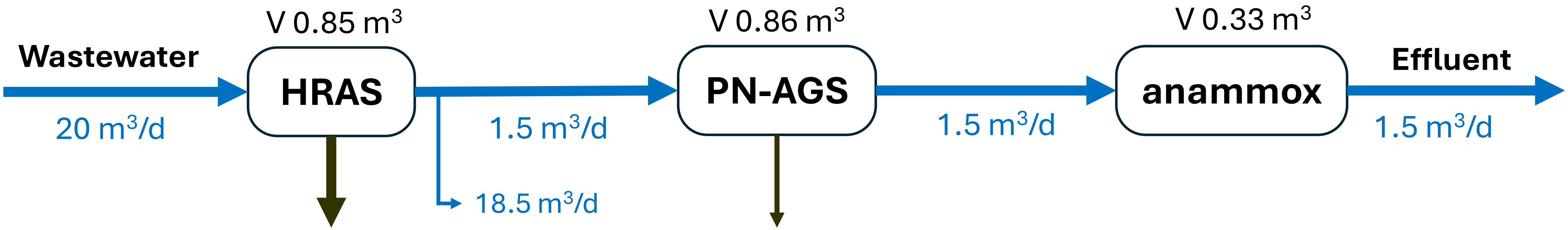
5. Mainstream partial nitritation with AGS

6. Mainstream autotrophic N removal from PN-AGS effluent

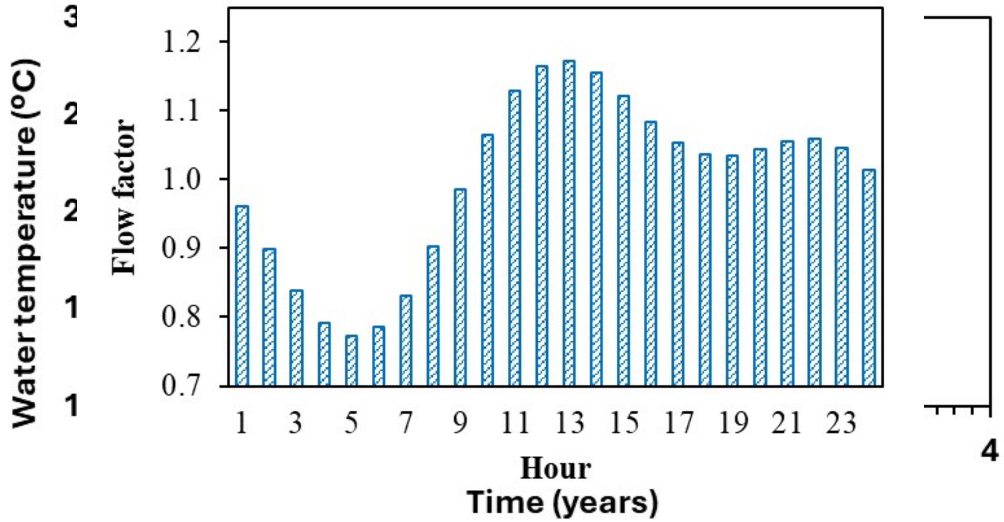
7. Energy balance: PROGRAMOX® vs. CAS

8. General conclusions

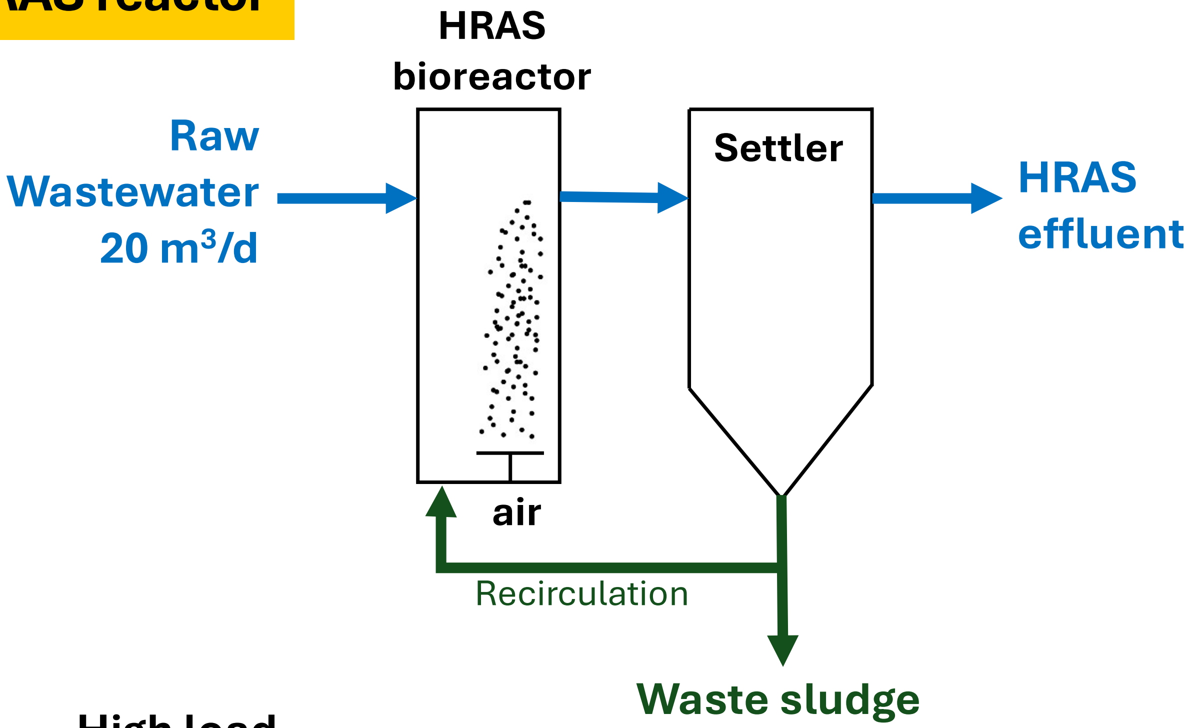
HRAS + PN-AGS + anammox mainstream pilot plant



- **Location**: La Garriga WWTP *(conventional WWTP near Barcelona)*
- **Influent**: raw pretreated wastewater *(before PS)*
- No temperature control (water **12-28 ºC**)



HRAS reactor



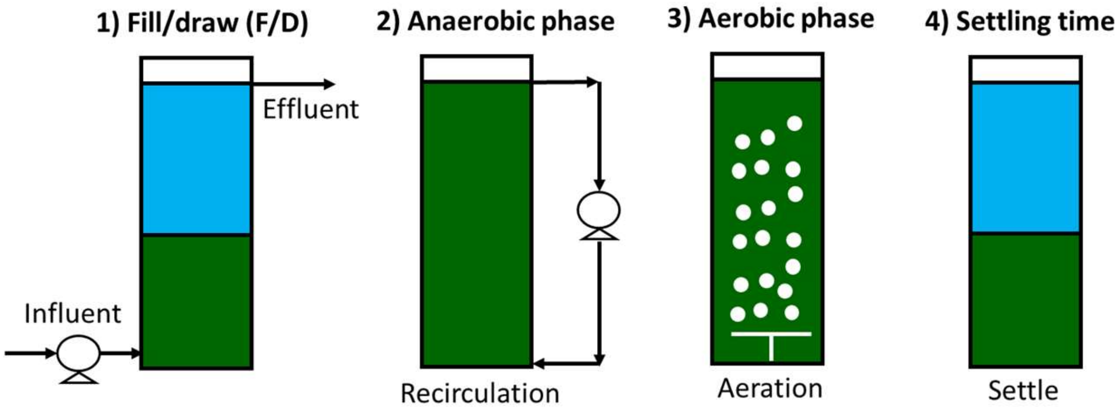
High load
- HRT 1 hour
- 2 g TSS/L
- SRT < 1 day

Low O_2 consumption
- 0.5 mg DO/L

- No inoculum

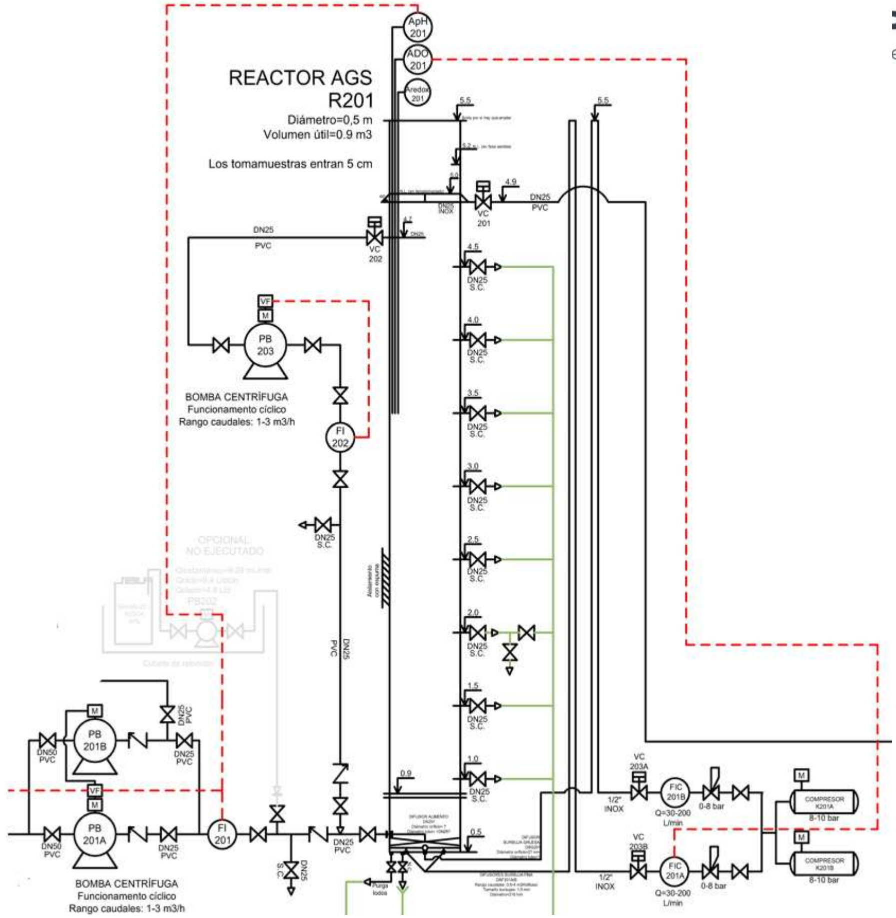
PN-AGS REACTOR

- ❑ **SBR** at **constant volume**



- Volume exchange ratio (**VER**): **50 – 60 %**
- **1.5 m^3/d, HRT 12-13 h**
- Aeration (fine+coarse): **2.0 mg DO/L**

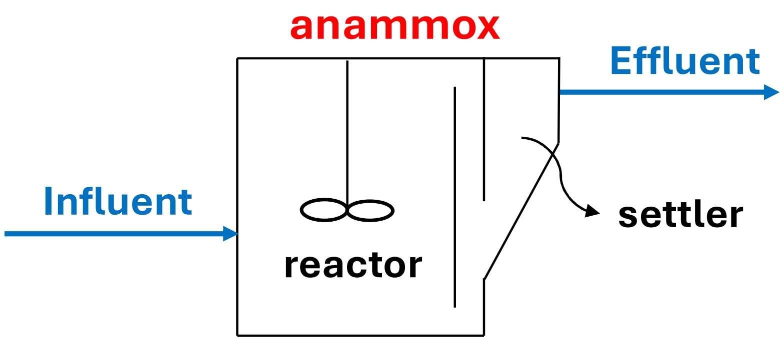
Inoculum: **floccular** activated sludge

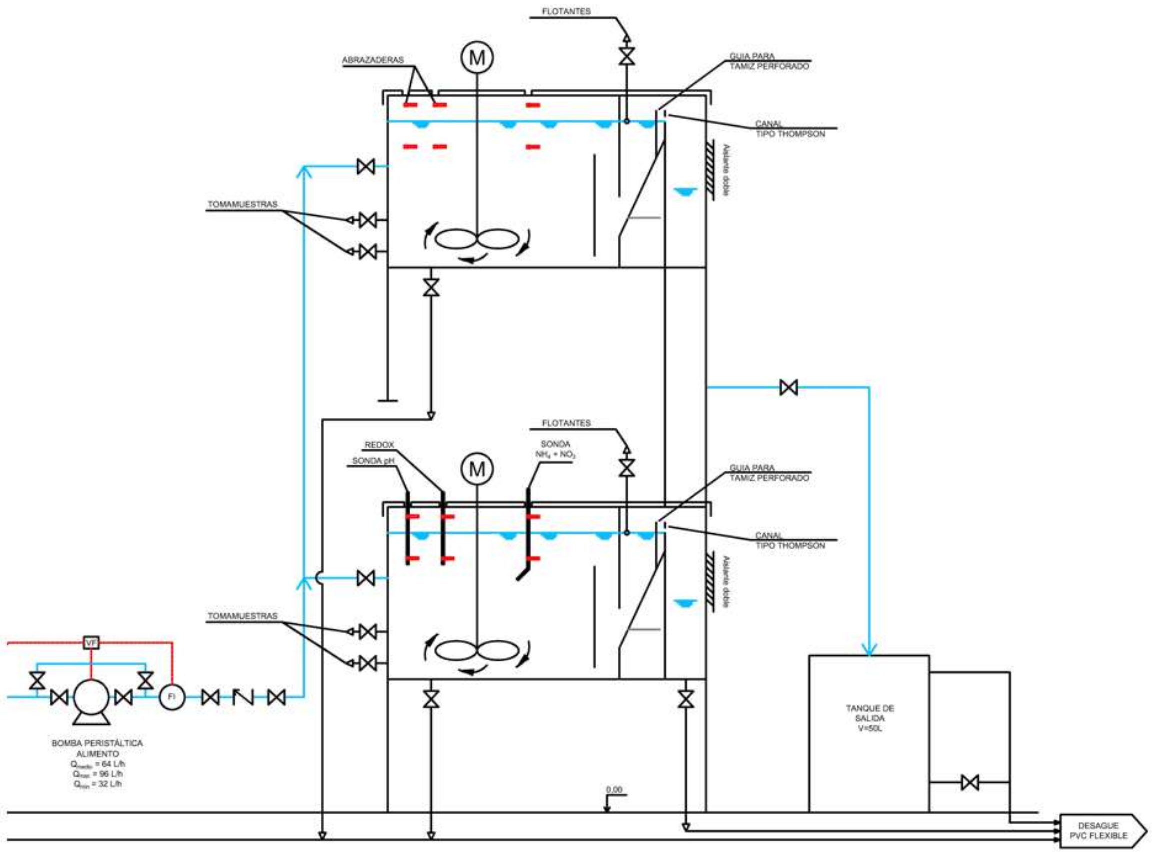


Height **4.5 m** (H/D = 9)

Anammox reactor

Continuous stirred tank reactor (**CSTR**) with **baffle settler**:





- **1.5 m^3/d, HRT 5 h**
- **Inoculum**: one-stage sidestream granular PNA biomass from Paques®
- **5 months** acclimation period
- Reactor solids content ca. **10 g VSS/L**

Analytical methods and sampling

- **Composite 24h samples** with automatic samplers (AS950, Hach): Influent and effluent samples. Once/twice a week
- **Spot samples**: Reactor's samples. Several times a week

- **TSS**, **VSS**, **SVI** and **alkalinity**: standard methods (APHA et al., 2017)
- **Anions** and **cations**: ion chromatography (ICS-5000, Dionex) and Hach Test N Tube (TNT) kits.
- **COD**: closed reflux and colorimetric method (Hach TNT kits)
- **Sludge size distribution**: sieving method *(van Loosdrecht et al., 2016)*
- **Sludge morphology**: stereomicroscope (Stereo Discovery V12, Zeiss)

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6. Mainstream autotrophic N removal from PN-AGS effluent

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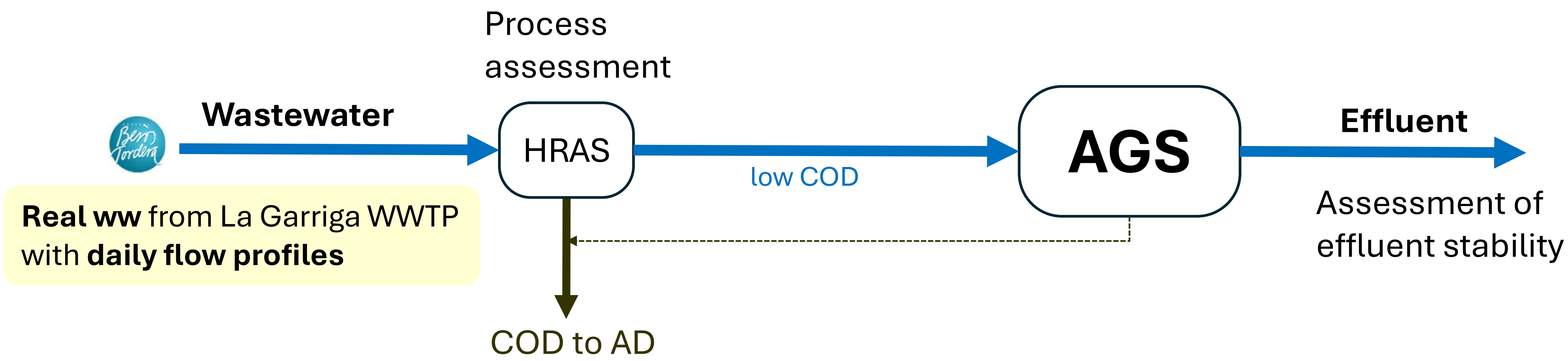
Motivation



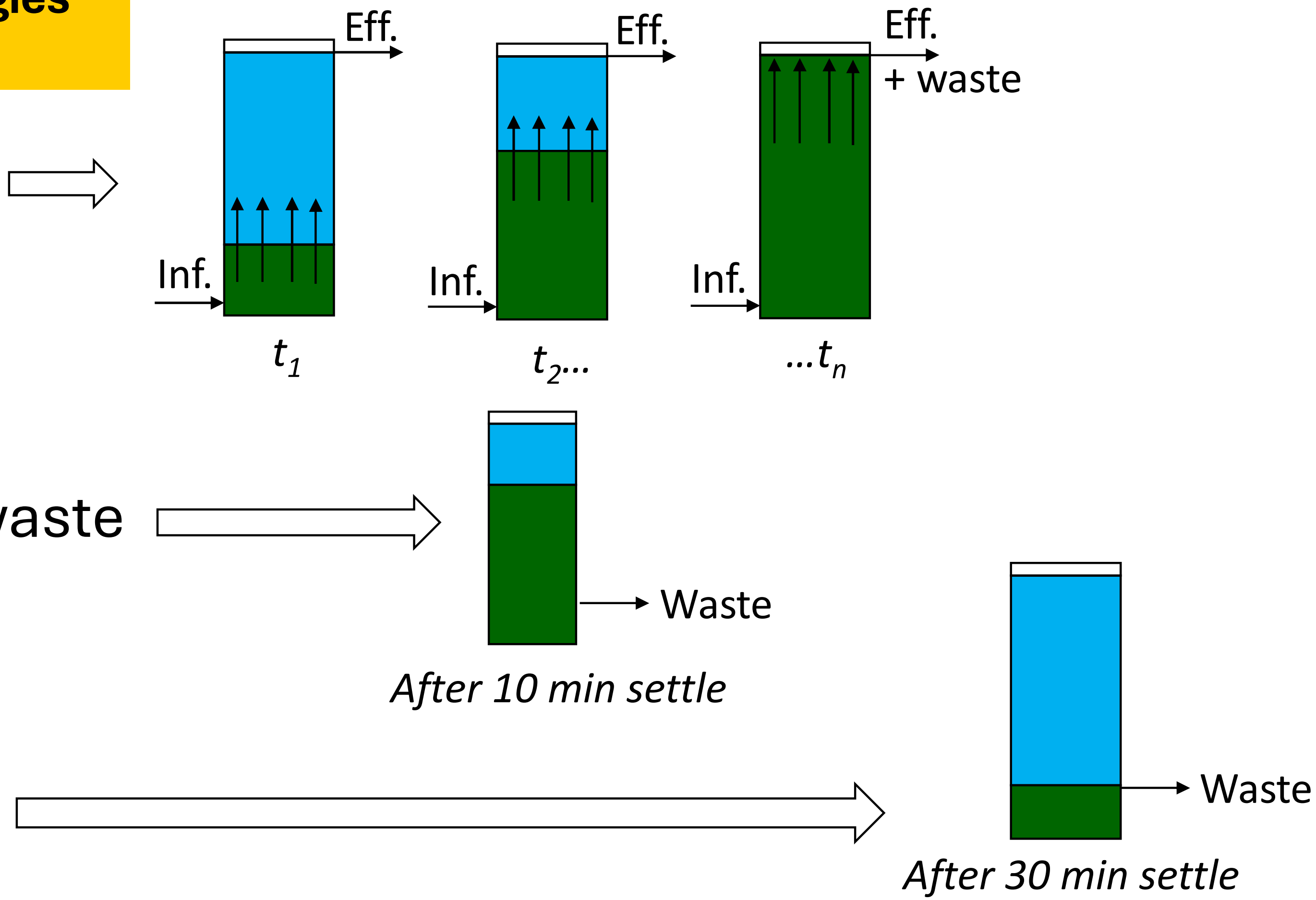
Identify a suitable strategy to **achieve AGS** from HRAS effluent (i.e., low COD and OLR)

AGS biomass waste strategies in views of granulation

a) Fill/draw waste

b) Intense lateral waste

c) Selective waste



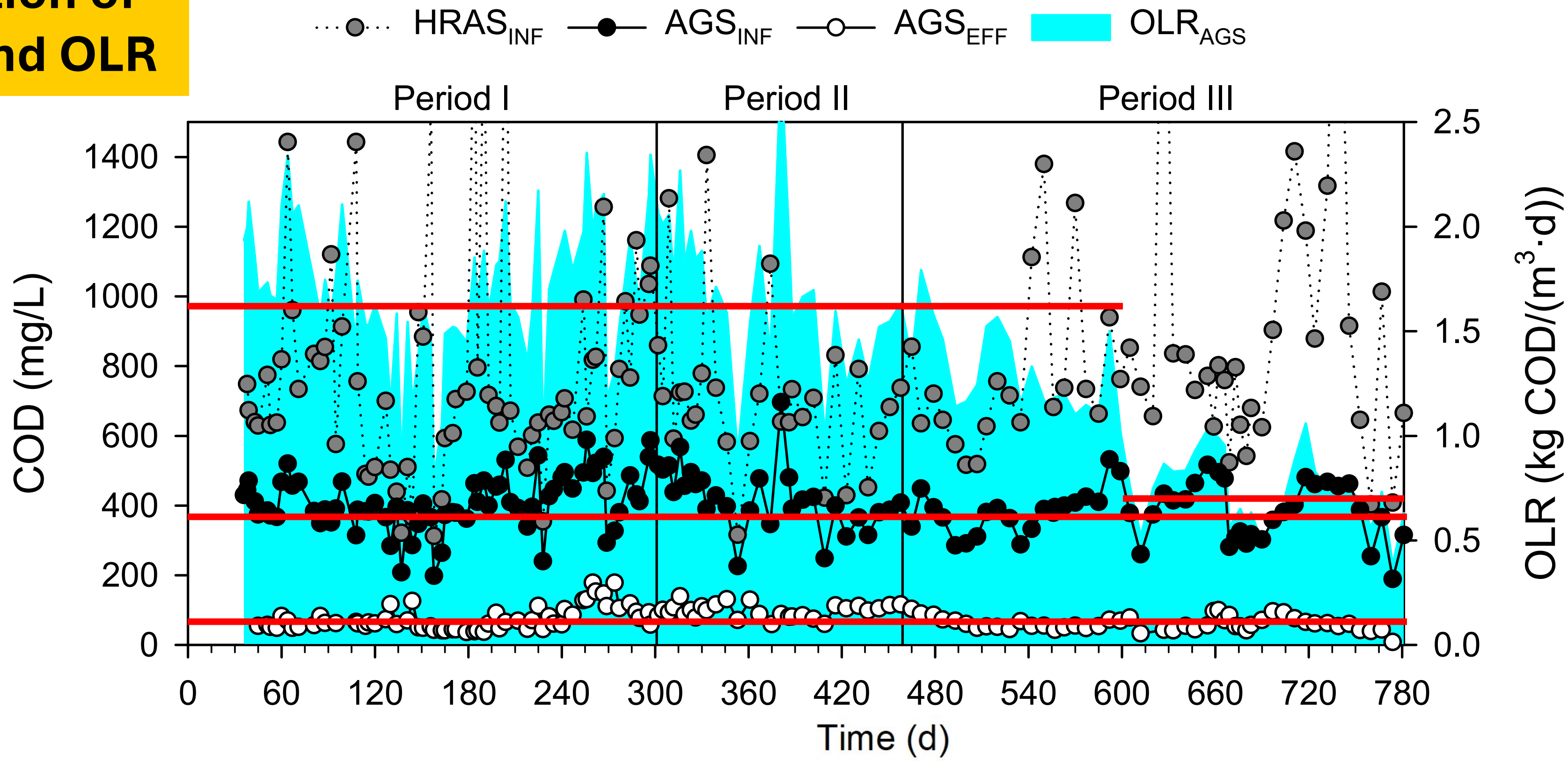
Operational periods

- 3 periods with 3 granulation strategies

Period	Biomass waste strategy	Day (d)	Cycle time (min)
I	(a) fill/draw	0 - 300	160 - 180
II	(b) intense lateral	301 - 458	180
III	(c) selective	459 - 781	180 - 360

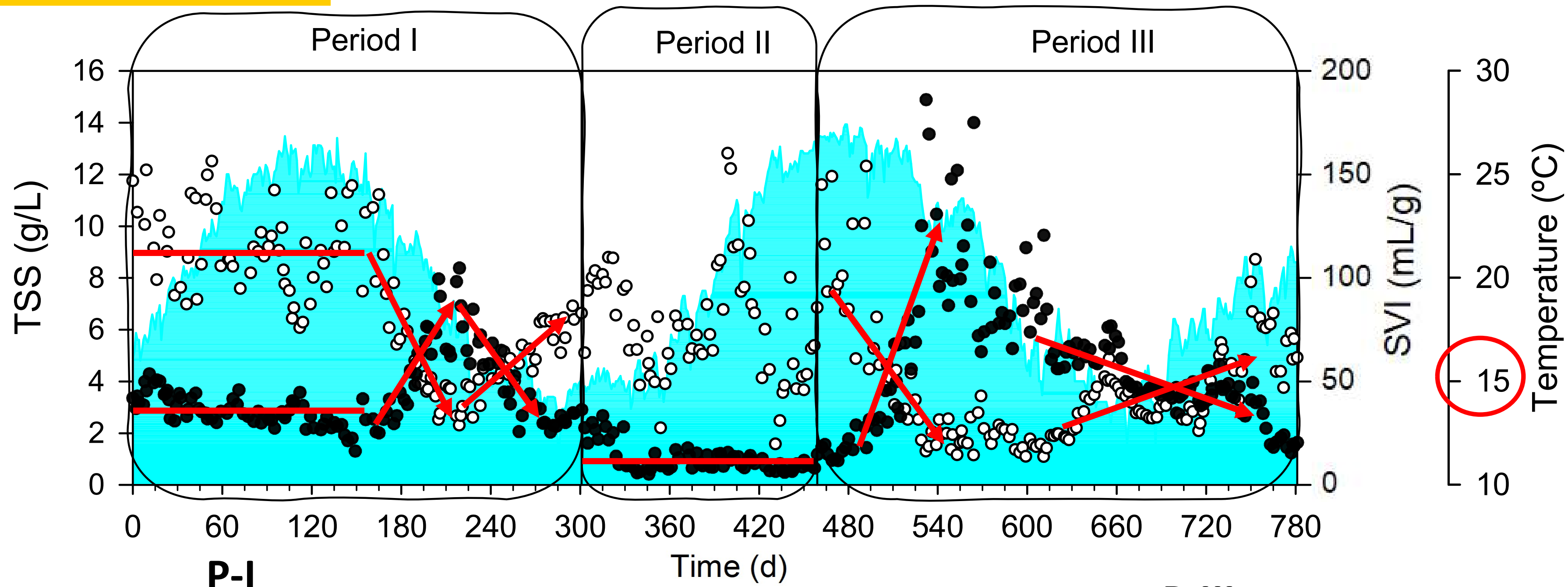
- **Period III**, cycle time extended for **nitrification** purposes

Evolution of COD and OLR



- ✓ AGS influent COD **391 ± 84 mg/L**
- ✓ AGS effluent COD **74 ± 30 mg/L**
- ○ OLR **1.6 ± 0.4 kg/(m³·d)** until day 600th
- ○ From day 600th OLR **0.7 ± 0.7 kg/(m³·d)**

Evolution of the reactor TSS and biomass settleability



P-I

Days	TSS (g/L)	SVI (mL/g)
0 - 150	2.9 ± 0.6	116 ± 23 mL/g
150 - 220	*up to* ***8.4 g/L***	*as low as* ***29 mL/g***
220 - 300	2.0 g/L	86 mL/g

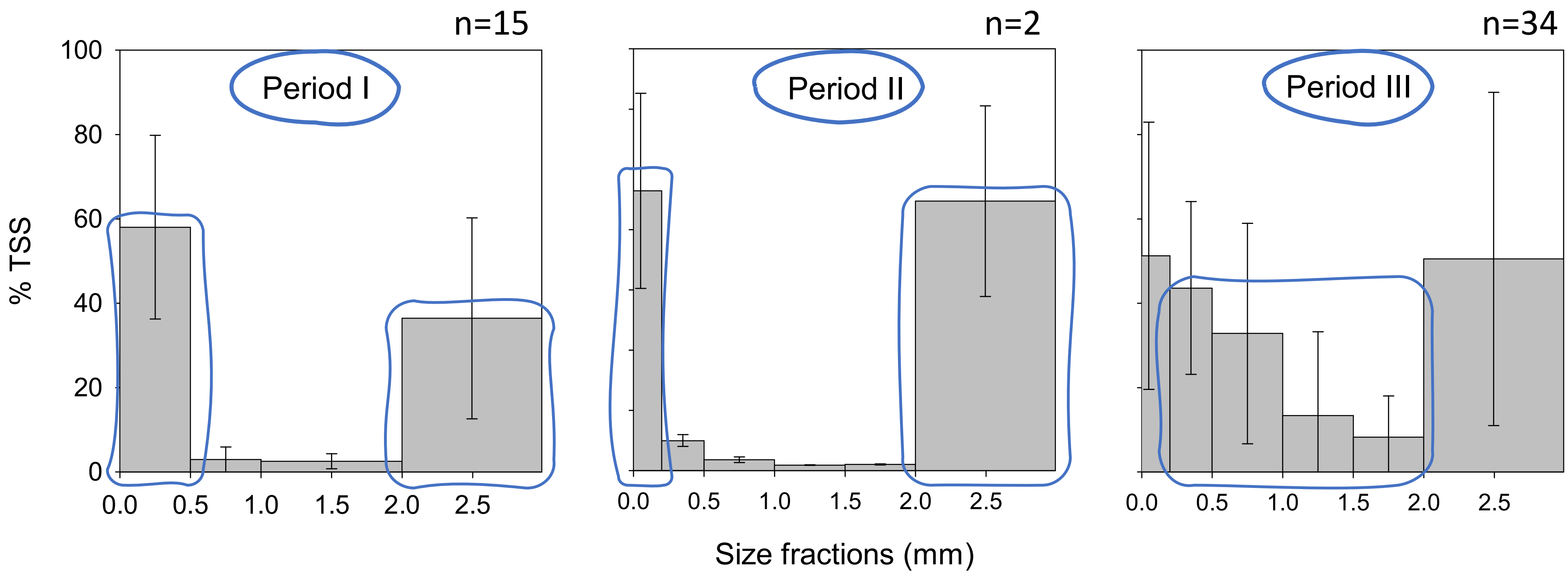
P-II

- TSS **1.0 ± 0.6 g/L**
- SVI from 20 to 160 mL/g

P-III

- TSS up to **14 g/L** with SVI of **20 mL/g** on day 540th, then gradual TSS reduction and SVI increase

Biomass fractions size distribution

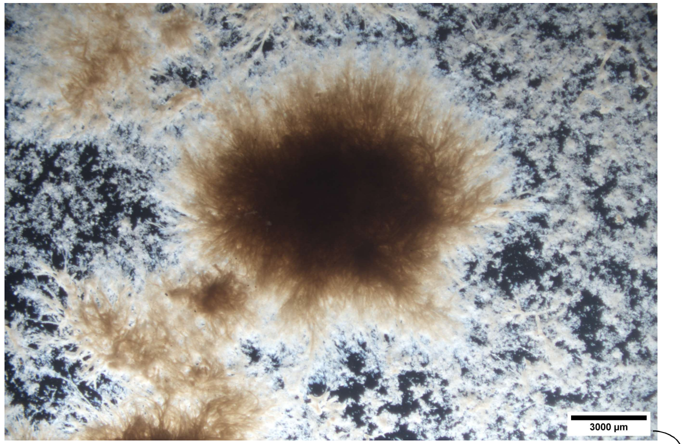


Periods I & II: coexistence of big aggregates (> 2.0 mm) and flocs (< 0.2 mm)

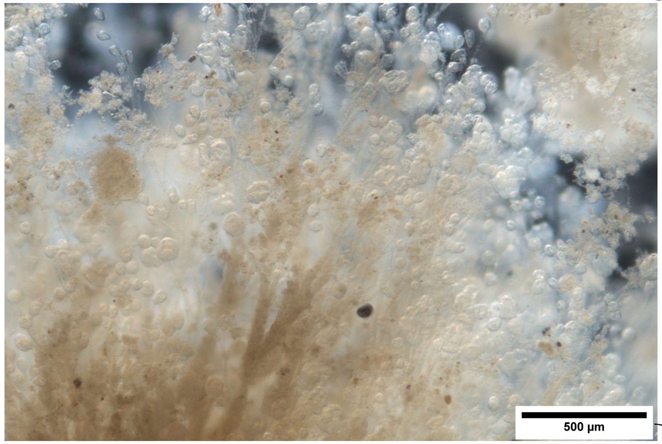
Period III: appearance of granular fractions (0.2 < TSS < 2.0 mm)

Microscope observations

PERIOD I: day 200th

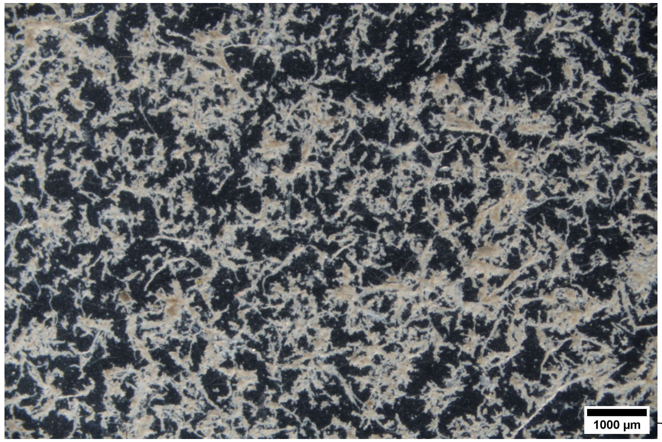


3000 µm



500 µm

PERIOD II: day 344th

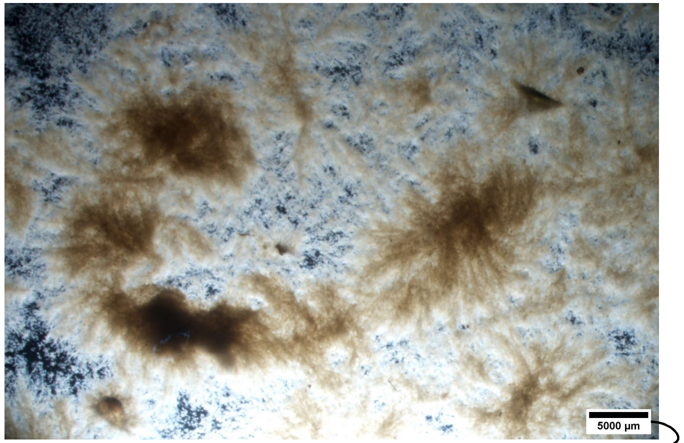


1000 µm

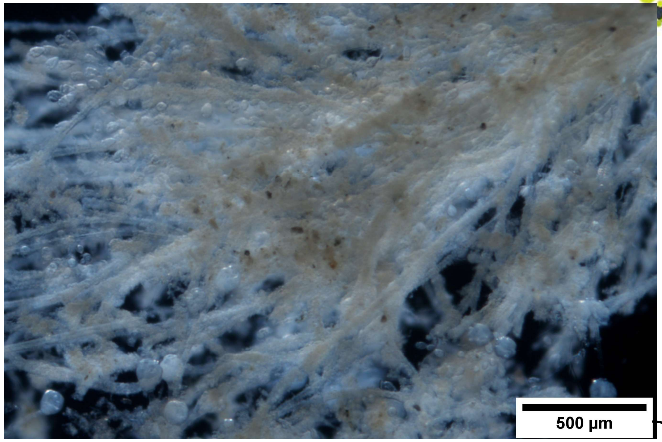
1000 µm

4. AEROBIC GRANULATION FROM HRAS

PERIOD III: day 512th

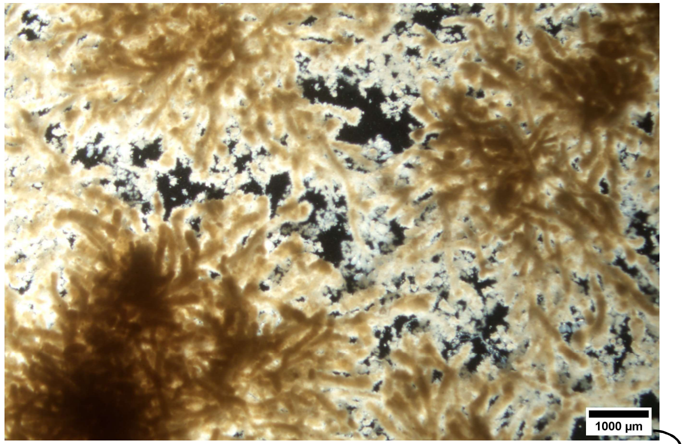


5000 µm

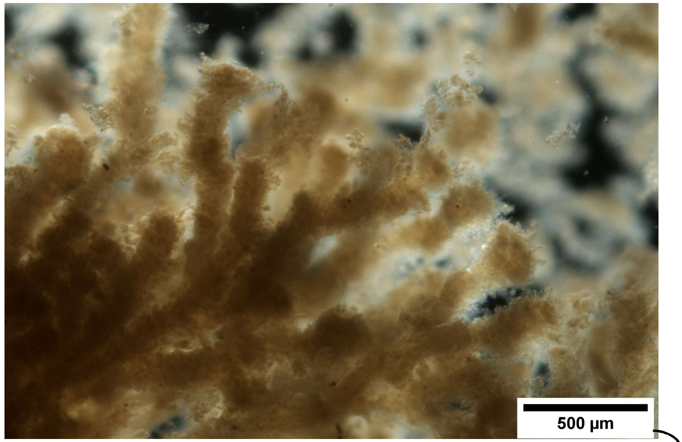


500 µm

PERIOD III: day 539th

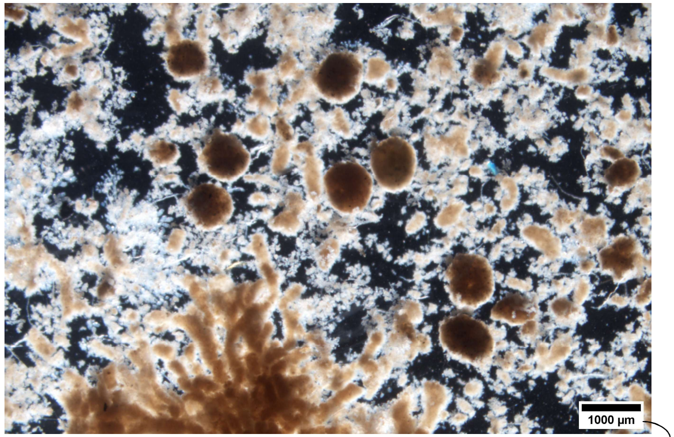


1000 µm

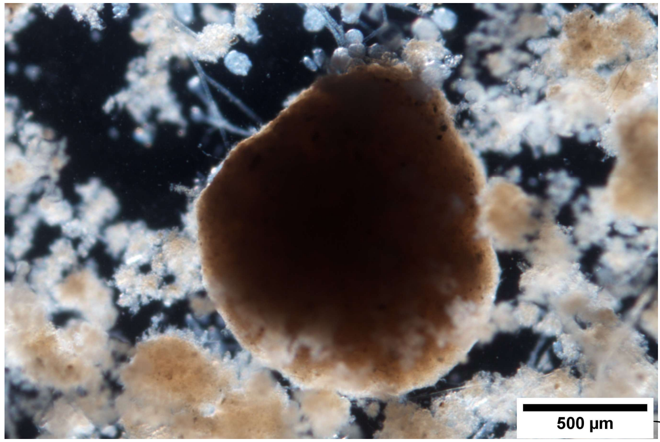


500 µm

PERIOD III: day 562th

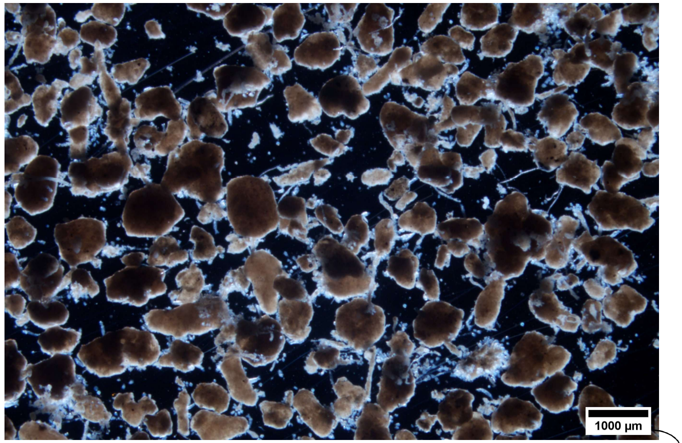


1000 µm

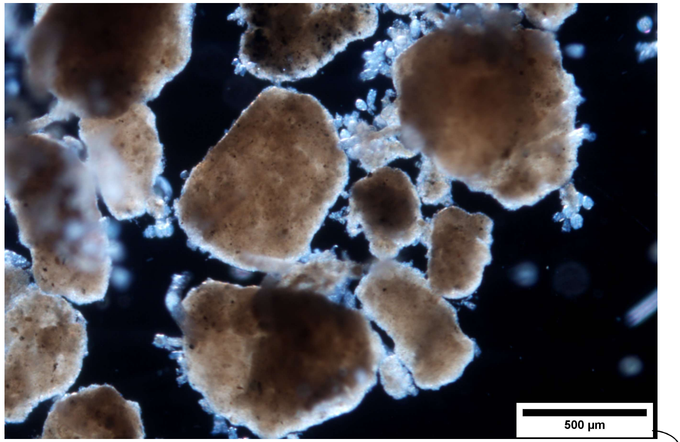


500 µm

PERIOD III: day 596th



1000 µm



500 µm

Conclusions

- ✓ Rather stable AGS **influent** (HRAS effluent) **COD** of **391 ± 84 mg/L** was observed
- ✓ Suitable strategy to achieve AGS from HRAS effluent:
  Selective wasting from the top of the settled sludge bed
- ✓ **Full granulation not crucial**
  Low SVI (< 100 mL/g, densified biomass) helpful enough for an operation with COD removal

RESULTS AND DISCUSSION

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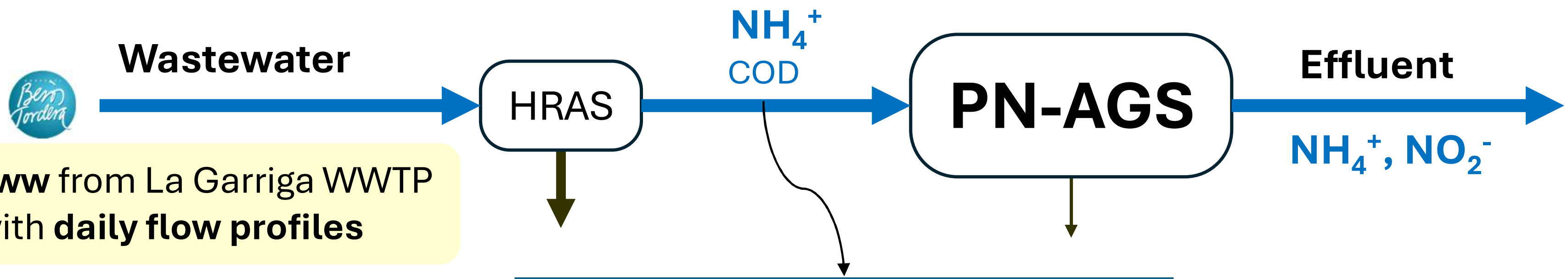
6. Mainstream autotrophic N removal from PN-AGS effluent

7. Energy balance: PROGRAMOX® vs. CAS

Motivation

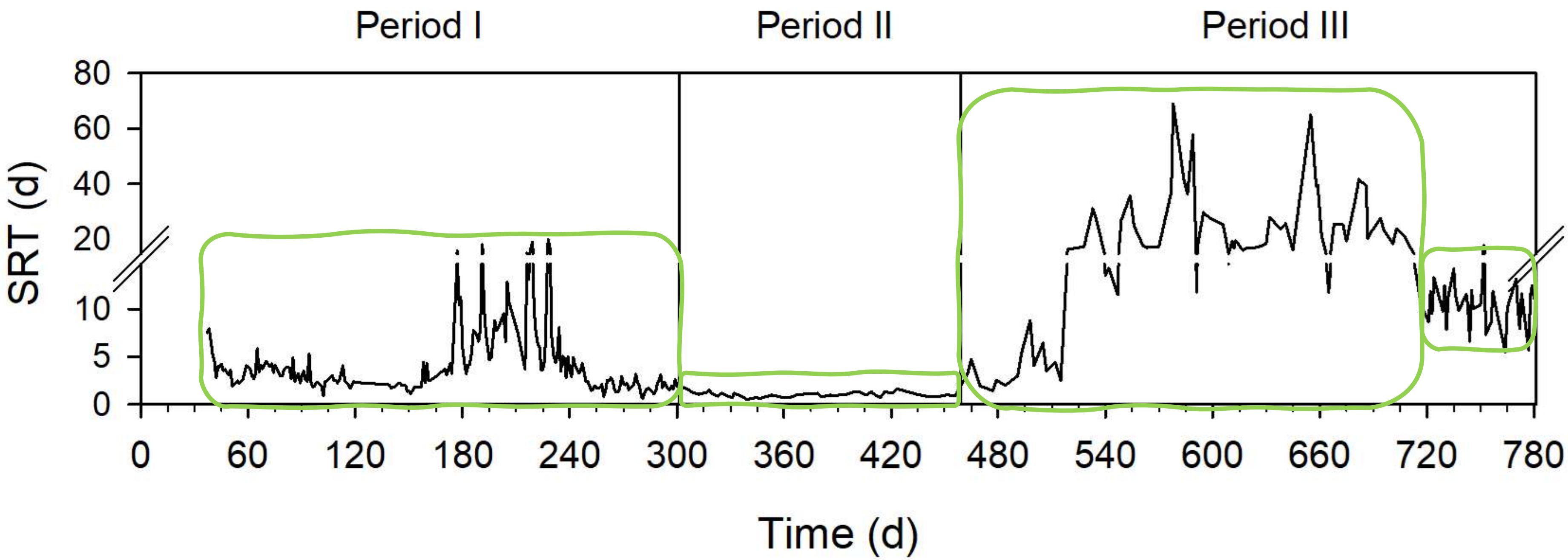


Real ww from La Garriga WWTP with **daily flow profiles**

Mean PN-AGS influent (HRAS effluent)	
COD (mg/L)	391 ± 84
NH_4^+-N (mg/L)	40 ± 13
PO_4^{3-}-P (mg/L)	4.5 ± 1.6
Alkalinity (mg $CaCO_3$/L)	359 ± 34

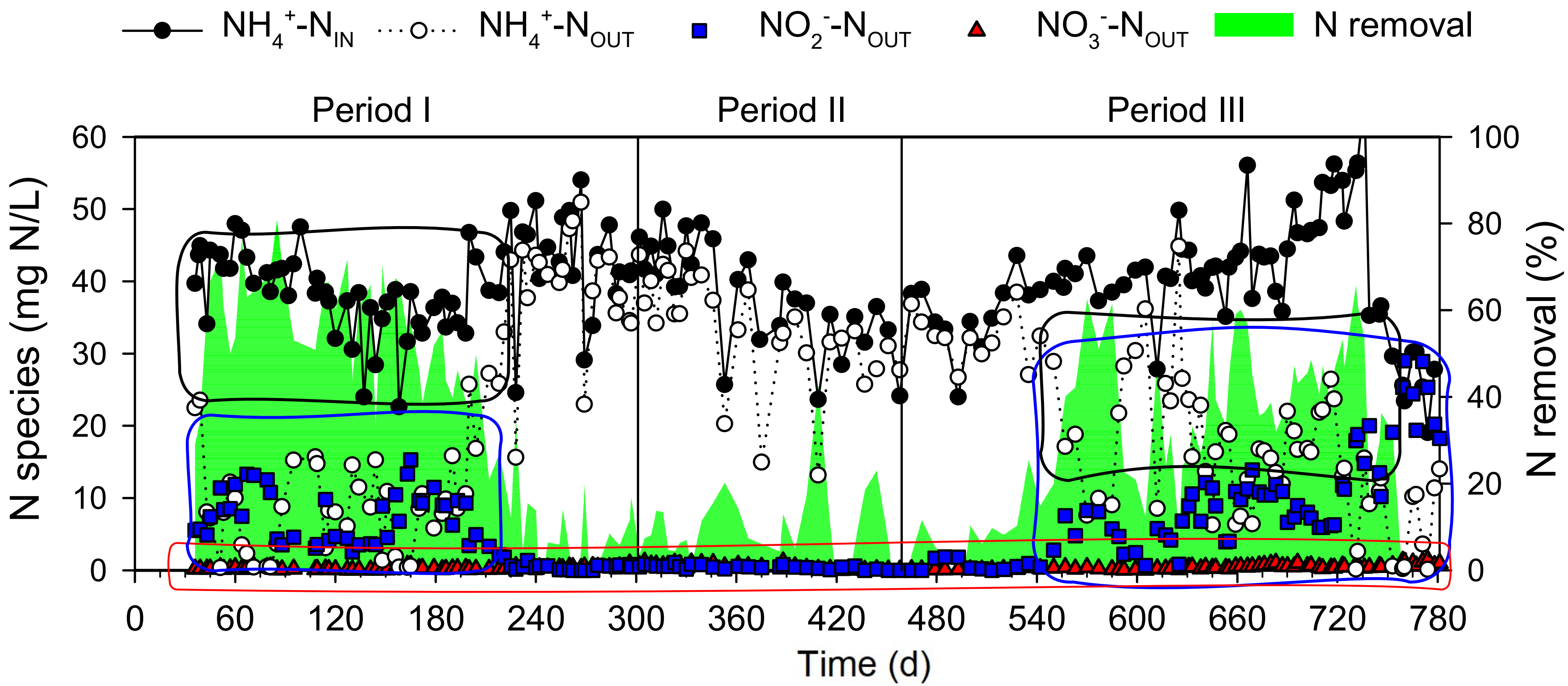
Achieve stable PN: effluent with NO_2^- and NH_4^+(without NO_3^-), NOB repression/washout

Evolution of the SRT in the PN-AGS



- P-I SRT of **4 ± 3 days**
- P-II SRT of **1 ± 0.3 day**
- P-III SRT **> 20 days** until day 720th, when it was controlled at **10 days**

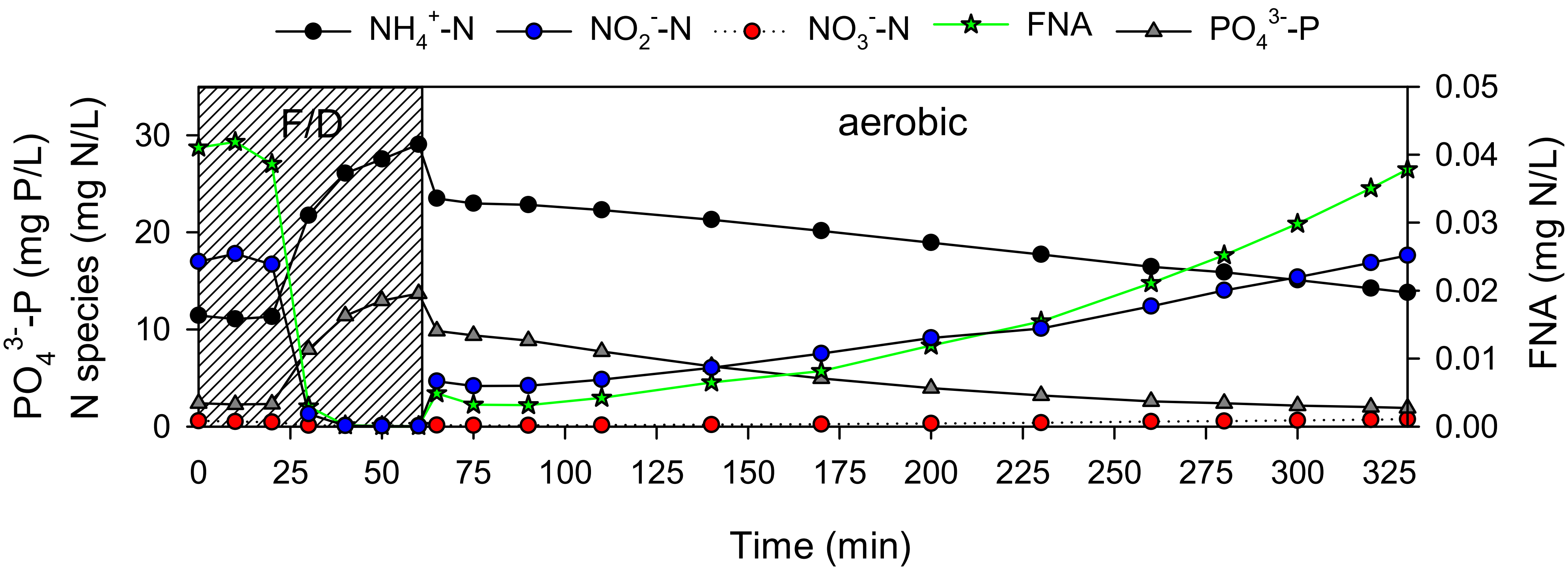
N-species and N removal in the PN-AGS



- NH$_4^+$ oxidation to NO$_2^-$ (nitritation) in Periods I and III, when SRT is high enough. **No NO$_3^-$ presence**
- Significative **N removal** in the PN-AGS. PI **57±15%** (flocs); PIII **37±16%** (AGS)

Which is the drive for PN?

Representative SBR cycle (Day 778th, Period III)



- Partial NH_4^+ oxidation without observed NO_3^- (i.e., **PN**)
- **FNA** values from 0.005 to **0.039 mg N/L** (pH 6.0-7.0) → **Inhibitory** to NOB
- P-release and P-uptake but high P content in the effluent

Blackburne et al. (2007)

- 50% NOB inhibition at **FNA** of **0.03 mg N/L**

Conclusions

- ✓ Stable PN was achieved at real mainstream conditions
- ✓ Operational conditions for PN in an SBR-AGS reactor after HRAS:
  - Bottom-fed F/D phase
  - DO in aerobic phases 2.0 mg/L
  - VER 50-60 %
  - HRT 12-13 h
  - Minimum SRT to foster nitrification and maximum 27 ± 15 d
  - **FNA** > **0.03 mg N/L**
- ✓ Granules not strictly necessary for PN (Period I)
- ✓ Granules reduced influent-biomass-NO_2^- contact and denitritation

Publication derived from Chapters 4 and 5

Carbó et al. (2024)
https://doi.org/10.1016/j.jwpe.2024.105165

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ELSEVIER

Achieving mainstream partial nitritation with aerobic granular sludge treating high-rate activated sludge effluent

Oriol Carbó [a,b], Jaume Teixidó [b], Joan Canals [b], Antonio Ordóñez [b], Albert Magrí [a], Mercè Baldi [b], Belén Gutiérrez [b], Jesús Colprim [a,*]

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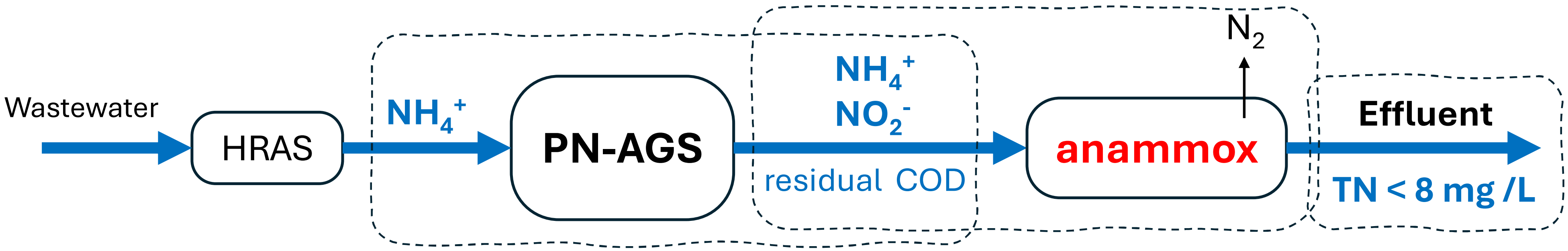
Motivation



PN control development and **assessment** with variability

Study the **performance** of the reactor

- Anammox **activity**
- **Role** of heterotrophic denitrification

Suitable effluent quality? **TN < 8 mg/L** (EU limit)

PN control strategy

$$NH_{4\_END} = \frac{NH_{4\_MAX}}{1 + Ratio}$$

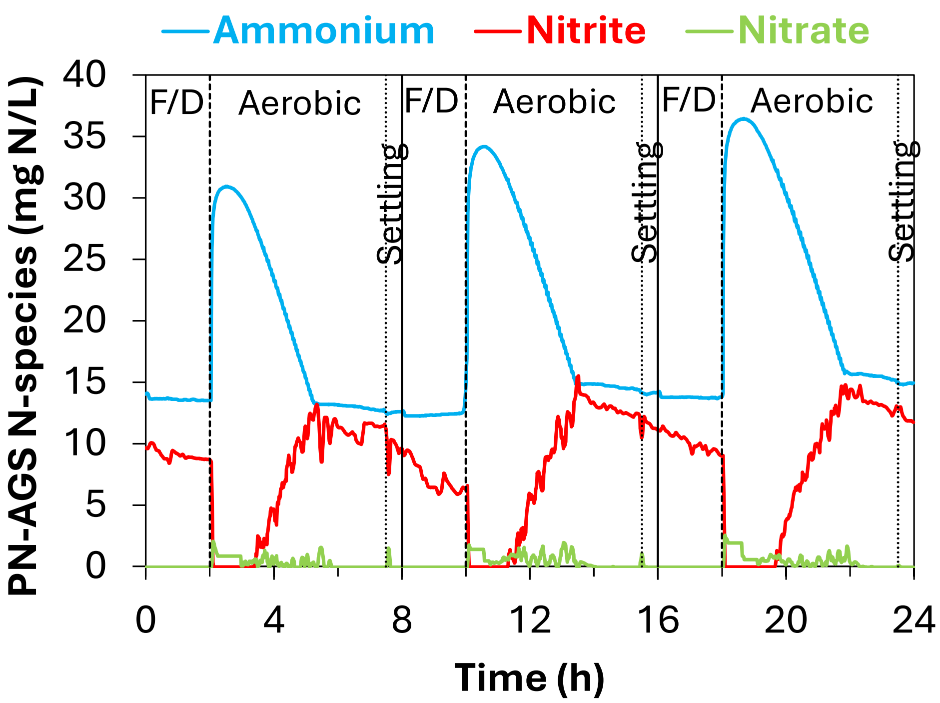
- NH_4^+ and NO_2^-+NO_3^- (NO_x^-) sensors installation

- Controlled variable: **NO_2^-/NH_4^+ Ratio**
- Measured variable: **NH_4^+**
- Manipulated variable: **aeration**

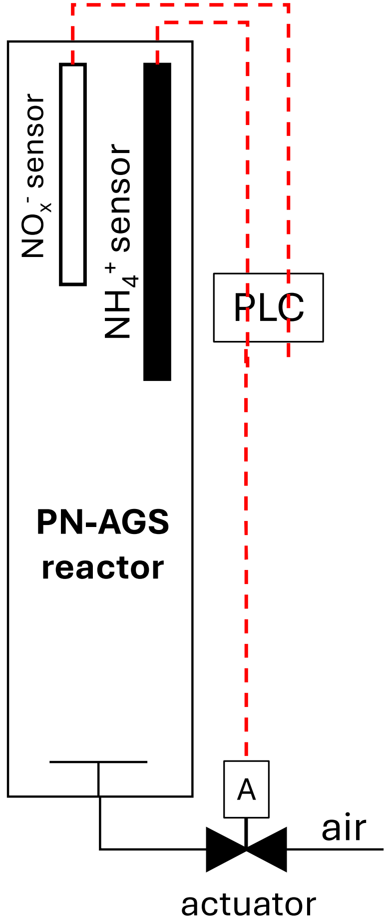
Control steps (aeration phase)

i. Identification of **NH_{4_MAX}** and calculation of **NH_{4_END}** to achieve the setpoint **NO_2^-/NH_4^+ Ratio**

ii. When NH_{4_END} is reached, air off

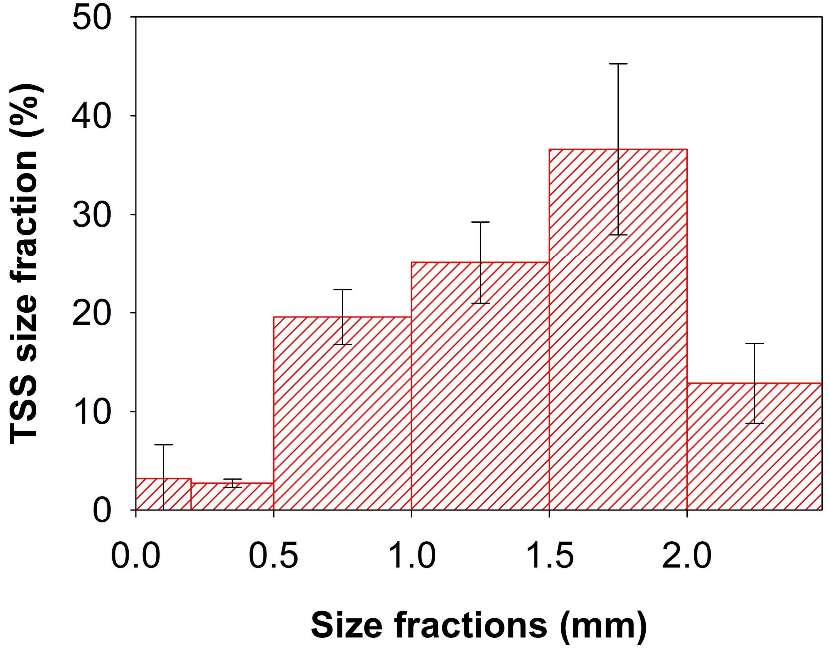


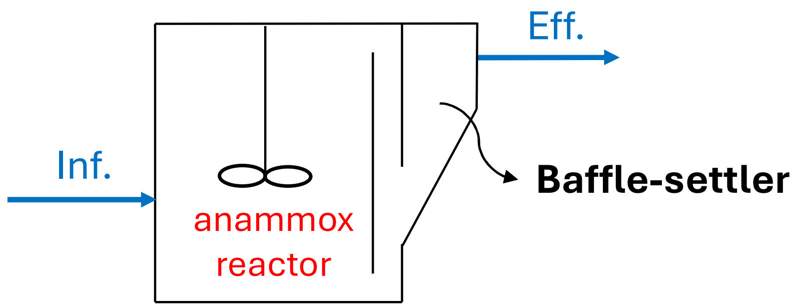
NO_x^- sensor only monitors



Anammox reactor operation

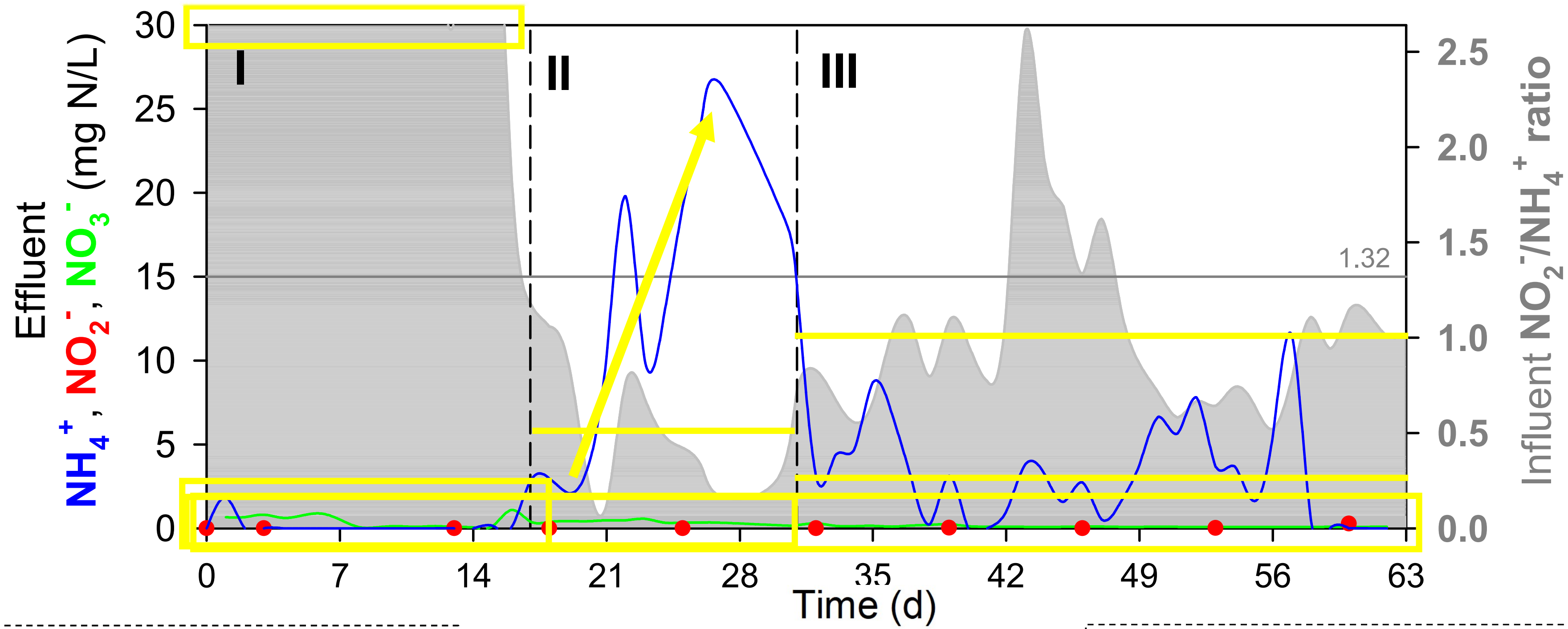
- Stable reactor TSS (despite not wasting): **11.6 ± 1.3 g TSS/L** (VSS/TSS 94%)
  - No accumulation
  - No washout
- Granular sludge, **TSS < 0.5 mm** less than **6 %**





✓ Correct solid-liquid separation

Anammox reactor operation



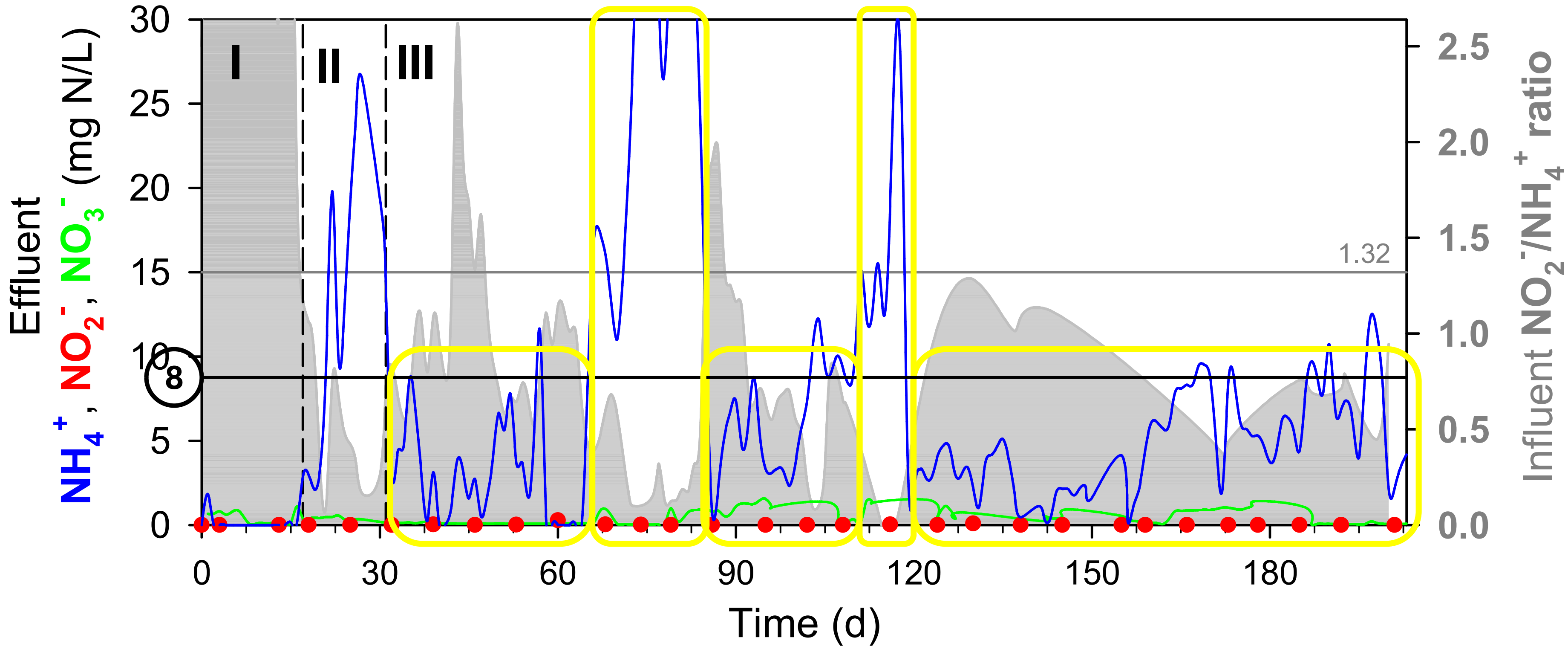
Phase I (control OFF)
- Inf. $NO_2^-/NH_4^+ > 2.5$
- ✓ Zero eff. NO_2^- and NO_3^-
  Het. denitrification

Phase II (control OFF)
- Inf. NO_2^-/NH_4^+ 0.5 ± 0.3
- Eff. NH_4^+ 14 ± 8 mg N/L
- ✓ Zero eff. NO_2^- and NO_3^-

Phase III (control ON)
- **Inf. NO_2^-/NH_4^+ 1.0** ± 0.5
- ✓ **Eff. NH_4^+ 3.2** ± 2.9 mg N/L
- ✓ Zero eff. NO_2^- and NO_3^-

Anammox reactor operation

Operation continues...



- Correct effluent quality, TN < 8 mg N/L
- Few instabilities

Conclusions

PN control

- ✓ A suitable strategy to control a desired effluent NO_2^-/NH_4^+ ratio was achieved.

Anammox

- ✓ **Coexistence** of anammox and het. denitrifiers helped **polishing** effluent NO_2^- and NO_3^-.
- ✓ Effluent suitable quality (**TN < 8 mg/L**) was achieved with $AMX_{INFLUENT}$ **NO_2^-/NH_4^+** of **0.80** or higher.

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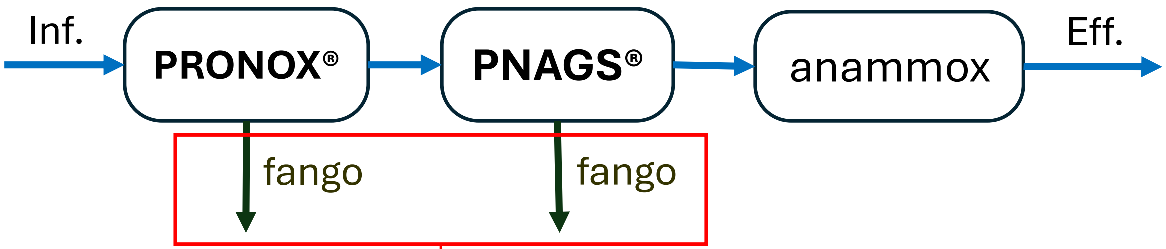
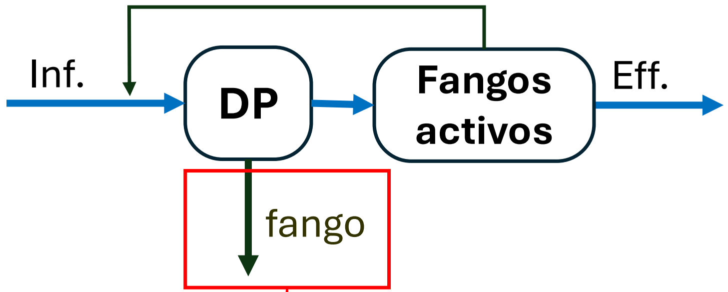
PROGRAMOX® vs. EDAR La Garriga: kWh/m^3 ?

PROGRAMOX®



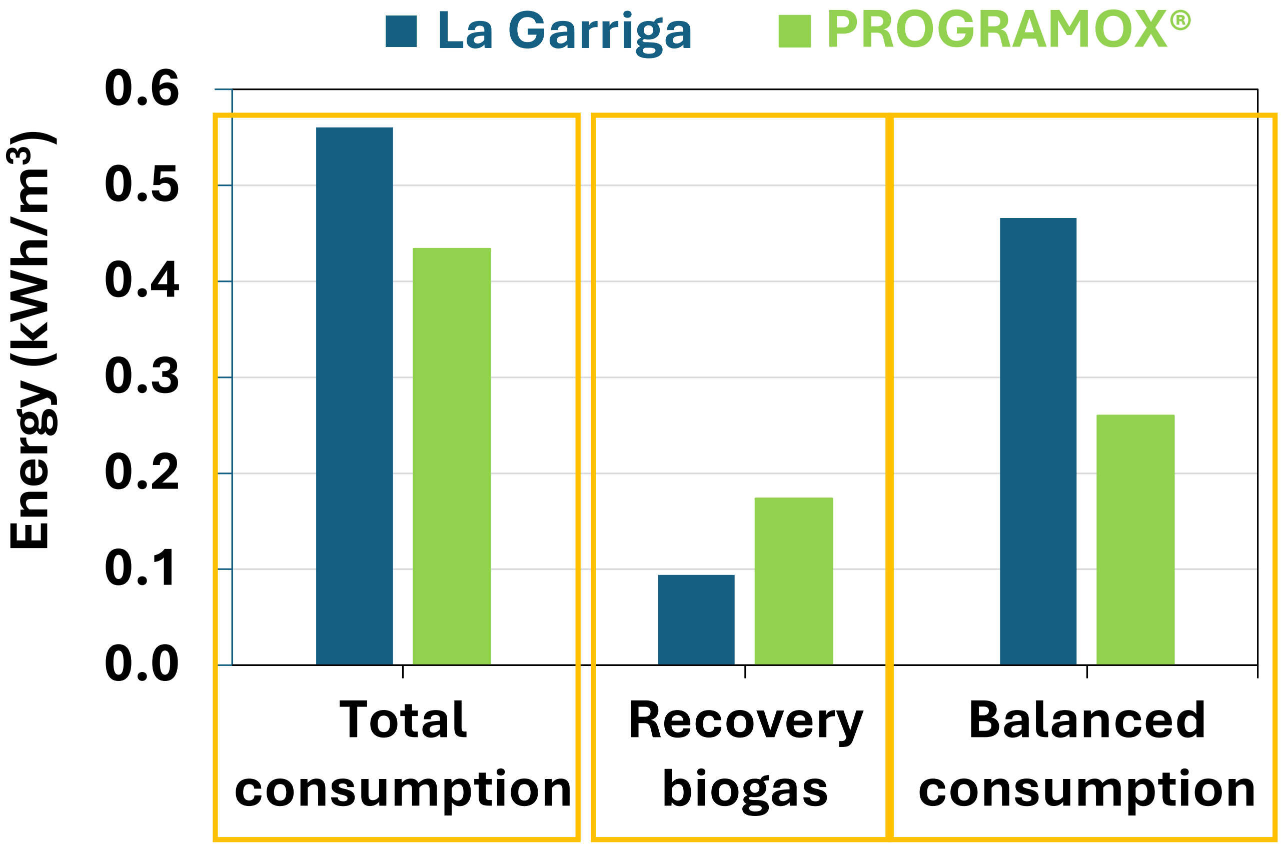
EDAR La Garriga



- Nitrificación-desnitrificación
- Adición $FeCl_3$ para eliminar P
- **Sin digestión anaerobia**

Potenciales de biometanización
fango PROGRAMOX® y La Garriga

Cálculo balance energético:
- **Datos experimentales**
- **Balances Q, DQO, SSV y N**



Configuración **PROGRAMOX®**:

- Consumo total **23%** inferior
  - **La Garriga**: **0.560** kWh/m³
  - **PROGRAMOX®**: **0.434** kWh/m³
- **84%** mayor recuperación energía CH_4
- Consumo balanceado **44%** inferior
  - **La Garriga**: **0.466** kWh/m³
  - **PROGRAMOX®**: **0.260** kWh/m³

✓ **Eficiencia**

8. GENERAL CONCLUSIONS

General conclusions

4. Aerobic granulation from HRAS

✓ Strategy to achieve AGS from HRAS effluent: selective wasting from the top of the settled sludge bed.
✓ Low SVI (< 100 mL/g, densified biomass) helpful enough for an improved operation with COD removal.

5. Mainstream partial nitritation with AGS

✓ Stable PN achieved at real mainstream conditions. Operational conditions were determined.

6. Mainstream autotrophic N removal from PN-AGS effluent

✓ A controlled PN-AGS effluent NO_2^-/NH_4^+ ratio was achieved despite flow/concentration fluctuations.
✓ Anammox effluent suitable quality was achieved with coexistence of anammox and het. denitrifiers.

7. Energy balance: PROGRAMOX® vs. CAS

✓ Significant energy saving could be reached if PROGRAMOX® was installed in La Garriga WWTP with AD.

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SPORE Med

MasterClass patrocinada por:
SMALLOPS Sustainable nanoenergy

Current/future work...

First **full-scale** PROGRAMOX® **demonstration** plant
- ❑ From 1.5 m^3/d to 400 m^3/d

PRIMA programme (EU funding)
- ❑ **SPORE-Med** project
  July 2024 – July 2027
  https://www.spore-med.eu/

EDAR Terrassa
- ❑ Place: old physicochemical
- ✓ Drawings done
- ✓ Construction done
- ➢ Start-up this summer

PRIMA
PARTNERSHIP FOR RESEARCH AND INNOVATION IN THE MEDITERRANEAN AREA

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Gracias por vuestra atención.
Y muchas gracias
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